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Invited Review

Supply chain management and advanced planning—basics, overview and challenges

Hartmut Stadtler

Fachgebiet Produktion & Supply Chain Management, Institut für Betriebswirtschaftslehre, Technische Universität Darmstadt, Hochschulstraße 1, D 64289 Darmstadt, Germany

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Abstract

Literature on supply chain management (SCM) covers several disciplines and is growing rapidly. This paper firstly aims at extracting the essence of SCM and advanced planning in the form of two conceptual frameworks: The house of SCM and the supply chain planning matrix. As an illustration, contributions to this feature issue will then be assigned to the building blocks of the house of SCM or to the modules covering the supply chain planning matrix.

Secondly, focusing on software for advanced planning, we outline its main shortcomings and present latest research results for their resolution.

Keywords: Supply chain management; Advanced planning; Advanced planning systems

1. Introduction

Since the introduction of the term supply chain management (SCM) in 1982 (see Oliver and Webber, 1992) it has received ever-growing interest both in the literature as well as from industrial practice. A reason for this might be that it has so many facets and that the tasks of accomplishing the aims of SCM are so demanding that it is more an ongoing endeavour than a single short-term project. This broad scope of SCM incurs the difficulty of finding a suitable definition and description of the term.

The aim of this paper is twofold: Firstly, we will provide an introduction to SCM by outlining those building blocks which incur some novel features for the management of (network) companies and hence play a major role in SCM. One of these building blocks, advanced planning, will be explained in greater detail. There are several commercial software packages available for advanced planning—so-called advanced planning systems (APS)—, which incorporate models and solution algorithms attributed to operations research. Since this paper also provides an overview of contributions to this feature issue we will assign these contributions to the building blocks of the house of SCM or to the modules of an APS (see Sections 2.2 and 3.2). As we will see (Section 3) there is a general structure of APS which best can be visualized by positioning its modules in a two-dimensional table, the SC planning matrix.

E-mail address: stadtler@bwl.tu-darmstadt.de (H. Stadtler).

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Secondly we are concerned with the future of APS. Therefore, we will highlight deficiencies of APS, which may give rise to future research. Three areas for improvements are proposed: Improvements which are possible within the modules of today's APS, issues which challenge the premises of today's APS, and last but not least two business functions are identified which should be better integrated with APS.

The structure of the paper is as follows. In Section 2 the term SCM is defined and its building blocks are described. Section 3 introduces the architecture and modules of today's APS. Issues and challenges of APS are presented in Section 4. A few comments conclude this paper (Section 5).

2. Essence and scope of supply chain management

2.1. The house of supply chain management

Following the proposal of Christopher (1998, p. 15) a supply chain (SC) '...is a network of organizations that are involved, through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hand of the ultimate consumer.' This definition stresses that all the activities along a SC should be designed according to the needs of the customers to be served. Consequently, the (ultimate) consumer is at best an integral part of a SC. The main focus is on the order fulfilment process(es) and corresponding material, financial and information flows.

In case the organizational units belong to one single enterprise an intra-organizational SC is given. Here, hierarchical coordination is possible and prevailing. While hierarchical coordination in globally operating enterprises is already a demanding task, the real challenge arises in an inter-organizational SC where hierarchical coordination is no longer possible.

Although there is a coherent view of what a SC represents, there are numerous definitions of the term SCM (see Otto and Kotzab, 1999). The definition proposed here is not totally new but tries to extract the essence of existing proposals: Supply chain management (SCM) is the task of integrating organizational units along a SC and coordinating materials, information and financial flows in order to fulfil (ultimate) customer demands with the aim of improving competitiveness of the SC as a whole. This definition is best visualized by the

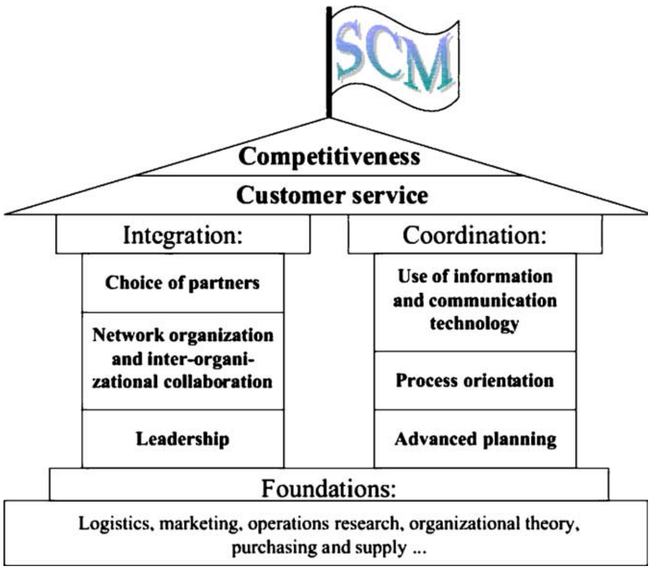

Fig. 1. House of SCM (Stadtler, 2002a, p. 10).

house of SCM (Fig. 1) and will be described in greater detail below.

2.1.1. Competitiveness and customer service

The roof of the house of SCM depicts the ultimate aim of SCM, namely improving competitiveness of a SC as a whole. This is achieved by directing the SC in a sustainable, strategic position compared to its competitors (this is in line with the ideas of Porter (1998, p. 55) for a single company). An important means to achieve this aim is customer satisfaction (see Christopher (1998, p. 35) for a detailed description). Excellent examples of how to focus SC processes on customers are given by two case studies (Berry et al., 1999; Childerhouse et al., 2002), which—based on the work of Skinner (1974)—show how to analyse the strengths and weaknesses of a SC in a competitive market. Concentrating on order qualifiers and order winners, a methodology is proposed for market segmentation followed by the re-engineering of a specific order fulfilment process for each market segment.

The roof of the house of SCM rests on two pillars, 'integration of organizational units' and 'coordination of flows'. Of the many facets of SCM we will outline three building blocks in each 'pillar', which we believe play an important and innovative role in SCM.

2.1.2. Choice of partners

Starting with the integration of organizational units we have to design the SC first, i.e. find those partners with the best fit to the existing SC and the needs of the customers to be served. At the very beginning the SC may consist of a single company taking the initiative. Due to the large efforts necessary to form a working SC usually only a small subset of all companies involved in the creation of a product or service for the ultimate consumer form a SC. Obviously geographical aspects will play an important role, the capabilities of potential partners—like product and process know how—as well as the financial position to name only a few. The fit might also be tested in the form of a due diligence (Berens and Strauch, 1999). This concept originates from public accounting and being used in mergers and acquisitions extensively advocates a thorough analysis of potential partners along several dimensions. These dimensions comprise the core competencies, trust, culture, strategy, organizational structure and financial situation (for a complete checklist see Ries, 2001, p. 337).

In contrast to a 'virtual company', which is often formed for just fulfilling a single customer order, a SC partnership is created in the medium-term, e.g. the lifetime of a product. This allows greater investments in close partnerships across the SC. The cooperation between partners in a SC should be such that each partner benefits—at least on a medium-term (so-called win–win situation). From a financial perspective this requires to adapt transfer prices negotiated within the SC and potentially to render compensation to partners, if asked to give up locally optimal decisions in favour of the SC as a whole.

2.1.3. Network of organizations

A SC can be regarded as a network of organizations with some common goals. The challenge in controlling such a network stems from the nature of relationships between SC partners. They are neither part of a single hierarchy nor loosely coupled by market relations. Hence, control mechanisms for a hybrid between market and hierarchy are looked for (e.g. Sydow, 1999). Also, a SC partnership always runs the risk of either separating (establishing e.g. market relations, if there are greater opportunities in short-term contracts) or being integrated into a hierarchy as a result of a take over. The latter may occur in case the SC runs the risk of losing a crucial partner. Based on a literature review Spekman et al. (1998) argue that the misfit of goals and strategies are frequent causes for the disintegration of networks (see also Skjøtt-Larsen, 1999).

A partnership between organizational units rests on daily decisions by employees and management. Although this statement is easy to make it is rather difficult to accomplish, considering that partners formerly may have experienced market relationships with information hiding, mistrust and perhaps even cheating. This is where the social sciences come into play, e.g. by analyzing how bonds can be created between interacting employees. These can be social, administrative or legal bonds to name only a few (see Håkansson and Johanson, 1990).

2.1.4. Leadership

The third building block concerns leadership within the SC. We only point out two extremes in the following, namely, focal and polycentric SCs (Wildemann, 1997). A focal SC is characterized by the presence of a partner who is the 'natural' leader, e.g. due to his financial power or exceptional knowledge of products and processes. Leadership then is similar to a hierarchy even if SC partners are legally separated (e.g. in the European automotive industry). In the other extreme, a polycentric network, all partners are regarded equal (e.g. in consumer goods manufacturing and retailing). Here, a steering committee might be appropriate for aligning decisions of partners, e.g. stipulating transfer prices and compensations. The steering committee might also have access to a SC-wide data and make use of SC-wide planning models (e.g. master planning), which are discussed in the following. In practice often intermediate states of leadership between the two extremes will prevail.

2.1.5. Information and communication technology

Building blocks enabling improved coordination of material, information and financial flows across the SC represent the second pillar of the house of SCM.

New opportunities of today's information and communication technology enable information exchange between partners within instants by means of the Internet and related services. Thus, sales data, forecasts, orders and any kind of messages can be exchanged across the SC immediately at low costs. Since information transmission constitutes a part of an order's lead-time, its reduction may also restrain the bullwhip effect (Lee et al., 1997). Furthermore, one has to mention the availability of Data Warehouses, which enable decision makers anywhere in the SC to store and retrieve historical mass data at a level of detail and in dimensions (e.g. time interval, geographical region and product type) most suitable for decision making.

2.1.6. Process orientation

Process orientation, the second building block of the coordination pillar, not only aims at tearing down barriers between business functions in order to accelerate the execution of processes and associated activities but also between organizations. In contrast to the original work of Hammer and Champy (1993) who propose a radical redesign of processes for gaining competitive advantage, incremental improvements are also looked for in SCs. Nonetheless, one should not stop with linking existing activities more effectively but also consider a redesign of processes, by eliminating duplicate or unnecessary activities. As Hammer (2001, p. 84) puts it 'streamlining cross-company processes is the next great frontier for reducing costs, enhancing quality, and speeding operations.'

2.1.7. Advanced planning

It is well-known that the strength of transactional enterprise resource planning (ERP) systems is not in the area of planning. Hence, APS have been developed to fill this gap. APS are based on the principles of hierarchical planning (Anthony, 1965; Hax and Meal, 1975) and make extensive use of solution approaches known as mathematical programming and meta-heuristics. More details about APS will be given in the next section.

In summary SCM is not a novel management paradigm as such. Instead it represents a new focus on how to link organizational units to best serve customer needs and to improve the competitiveness of a SC as a whole. In this endeavour SCM has drawn knowledge and approaches from a number of disciplines like computer science, logistics, marketing, operations research, organizational theory and many more. To extract, adapt and combine those approaches which best suit a specific SC is the challenge of managing a SC successfully (Simchi-Levi et al., 2003).

The importance of the building blocks of SCM presented above is supported by empirical studies, pointing out that these represent major success factors in today's business (e.g. Fawcett and Myers, 2001; Pfohl and Mayer, 1999; Ramdas and Spekman, 2000). The only exception is 'advanced planning' which has not been addressed in the empirical studies. Instead the role of its predecessor—enterprise resource planning (ERP)—has been investigated.

Next, we will assign the contributions of this feature issue to the house of SCM wherever possible.

2.2. Assigning contributions of this feature issue to the house of SCM

It has been argued that customer service has several dimensions. Traditionally, inventory theory considers one dimension, namely performance measures related to the customer demand that can be fulfilled instantaneously (from stock). Accordingly, Nielsen and Larsen (2005) deal with joint replenishments of several retailers from a single warehouse analytically by means of a Q(s,S) policy. They show that the Q(s,S) policy is at least as good as other policies proposed for this decision problem. Service considerations also play an important role in a spare part distribution network including repair shops where a target system availability has to be achieved. Here, Sleptchenko et al. (2005) extend the well-known VAR-METRIC method.

The structure of SCs as well as decision problems in specific lines of business are addressed by Persson and Göthe-Lundgren (2005) (oil industry) as well as Carlsson and Rönnqvist (2005) (forest industry).

Inter-organizational collaboration is the concern of two papers: Dudek and Stadtler (2005) devise a negotiation scheme for aligning master plans between a buyer and a supplier based on the assumption of a fair exchange of (order) information without cheating. Corbett et al. (2005) analyse purchase contracts for indirect materials in a situation of double moral hazard and propose an incentive scheme (shared savings) that lead to a greater efficiency for the SC (buyer and seller) as a whole.

While traditional SCM focuses on the order fulfilment process in primary markets the paper by Robotis et al. (2005) extends it to remanufacturing and secondary markets (e.g. for used mobile phones). They address issues like the cut-off quality level of a product to be remanufactured instead of being disposed.

In the following we will further explore one building block, advanced planning. Contributions to this building block are indicated in Section 3.2.

3. Architecture of APS

3.1. The supply chain planning matrix

Although developed independently by different software vendors APS exhibit a common architecture based on the principles of hierarchical planning. The main focus is on supporting the material flow across a supply chain and related business functions: procurement, production, transport and distribution as well as sales (see Fig. 2, *x*-axis).

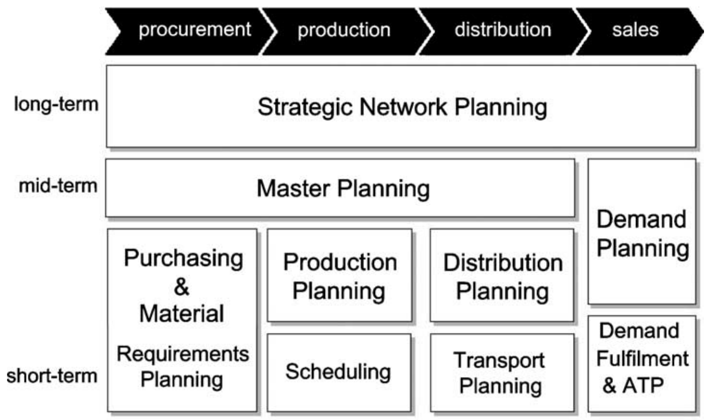

Fig. 2. Software modules covering the SC planning matrix (Meyr et al., 2002, p. 99).

The associated planning tasks can be considered at different levels of aggregation and planning intervals ranging from 'aggregated long-term' to 'detailed short-term' planning (see Fig. 2, *y*-axis). These two axes form the SC planning matrix. Its contents are planning tasks, which also correspond to software modules constituting an APS.

These planning tasks and associated functionality of software modules will now be described briefly.

3.1.1. Demand planning

Since SCM is driven by demand, the starting point of planning are available and planned customer orders. The longer the planning horizon the greater the portion of forecasted demand. Apart from well-known methods for univariate time series—like Winters exponential smoothing for seasonal and trend demand (Silver et al., 1998)—there are also multivariate methods and life cycle models. The step from pure demand forecasting to demand planning is made by adding to the formal demand forecasts those exceptional influences expected to happen in the future and their impact on sales. These events may either be controlled by members of the SC itself (like promotions) or to be subject to competitor actions (like the introduction of a new product) or by neutral parties (like a football world cup).

Expected demands are input to several modules in various aggregations and forecast intervals.

3.1.2. Strategic network planning

A planning interval of several years can be assumed when designing the structure of a SC. Here the location of production sites, warehouses, geographical customer areas to serve are laid out. Also, the capacity of these facilities as well as the transportation means (ships, trucks, railway, etc.) to use are decided upon.

3.1.3. Master planning

Given the structure of the SC, master planning looks for the most efficient way to fulfil demand forecasts over a medium-term planning interval, which often covers a full seasonal cycle. Master planning not only balances demand forecasts with available capacities but also assigns demands (production amounts) to sites in order to avoid bottlenecks. Due to the medium-term planning horizon it is often possible to adjust available capacities to a certain extent (e.g. by overtime). As regards procurement, some purchased items may become a bottleneck too, which then have to be considered as a restriction to master planning. However, in the majority of cases, the amounts to be procured can be derived ex-post from master planning and may result in special arrangements with suppliers (e.g. standing orders). Whether lot-sizing has to be incorporated explicitly into master planning largely depends on the relation of an item's expected time between orders (TBO) and the length of a period in master planning. If the TBO is larger than a period, lot-sizing has to be taken into account, because otherwise the time between lot-size productions (orders) of an item proposed by master planning may be reduced to a single period.

3.1.4. Production planning and detailed scheduling

While master planning coordinates flows between sites, production planning and detailed scheduling is run within each site, or even each production department based upon directives of master planning. In production planning the level of detail are shifts, machine groups or flow lines which may become a bottleneck and operations to be performed on these potential bottlenecks. In case the loading of machine groups—including lot-size decisions—is strongly affected by the sequence of jobs both production planning and detailed scheduling should be performed simultaneously (which often applies to the process industry).

3.1.5. Purchasing and material requirements planning

Master planning as well as short-term production planning and detailed scheduling provide directives for calculating procurement quantities to be planned within the module purchasing and material requirements planning. After disaggregating product types or product families into items a bill of materials (BOM) explosion is applied to derive required quantities of procured items.

Furthermore, this module is needed in the short term for planning of non-bottleneck operations because only potential bottleneck operations are planned for in production planning and detailed scheduling. In order to find out which operations have to be performed at which points in time also a simple BOM explosion is executed. Here, planned production amounts of potential bottleneck operations are fixed and build the starting point of the BOM explosion. Capacity considerations may be omitted by definition of a non-bottleneck operation. Hence, a given lead-time offset should suffice.

3.1.6. Distribution planning

So far we have mainly concentrated on production operations. Now the flow of goods between sites as well as in the distribution network comes into play. Seasonal stock levels at different stocking points in the SC have already been planned for in master planning. Here, we have to take care of transports of goods to customers (directly) as well as via warehouses and cross docking. This now happens at a greater detail than in master planning. In case production amounts do not exactly match a current period's demand, rules and procedures are applied to guide the flow of goods within the SC (e.g. in the case of scarcity transport of goods will be such that target inventories of an item at different distribution centres are filled at an equal percentage).

3.1.7. Transport planning

Based on production orders to be completed the next day (or shift) truckloads for different destinations have to be formed (so-called vehicle loading). This also requires detailed knowledge of outstanding orders from warehouses and customers. Also, the specific needs of customers (like time windows for delivery) and legal restriction for drivers have to be obeyed. Sequencing customer locations on a vehicle's trip is accomplished in (models of) vehicle routing. However, there is a trend in Europe towards utilizing a third party logistics provider (3PL) for transportation. Often a 3PL can consolidate orders from different SCs, thus the above planning tasks are executed by the 3PL himself with the help of special purpose software.

3.1.8. Demand fulfilment and available-to-promise

Last but not least there is the interface to the customers via the demand fulfilment and available-to-promise module. One task is to track customer orders from order entry, via order execution to order delivery. Furthermore, order promising, due date setting and shortage planning are considered here.

Order promising starts with matching available inventory and expected supplies—as known from master planning—with already committed customer orders. Remaining quantities are the available-to-promise (ATP) quantities which can be used for promising due dates for (new) incoming orders. If ATP quantities are insufficient, orders can be promised on the basis of capable-to-promise (CTP) quantities, indicating the slack capacity remaining after matching available capacity with already committed customer orders. In case of unforeseen events, like a breakdown of machines, shortage planning comes into play, specifying which (committed) customer orders will not be served in time. Only simple rules are implemented in standard software so far (Fischer, 2001; Kilger and Schneeweiss, 2002).

It should be noted that despite the general description, software vendors also offer additional modules for the specific needs of industrial sectors, like a car sequencing module to be used for controlling final assembly lines in the automobile industry.

Advanced planning is not an isolated building block of SCM; instead it should be used for decision support within other building blocks: e.g. the choice of partners in different geographical regions can be evaluated by strategic network planning. Different proposals from partners for the best utilization of available resources within the SC can be compared as alternative master plans and contrasted with globally optimal plans. These master plans may be generated for discussions in a steering committee (see leadership building block). Hence, there should be no surprise, that some contributions to this feature issue will be listed both in Section 2.2 and in the next subsection where we assign them to the modules covering the SC planning matrix.

3.2. Assigning contributions of this feature issue to the SC planning matrix

Spitter et al. (2005) present a novel approach for modelling lead times within master planning, where an operation can be executed at any time within its fixed lead time offset. This greater flexibility can lead to a much better utilization of resources (machines). Dudek and Stadtler (2005) consider an inter-organizational SC where master planning is performed decentrally. A negotiation-based procedure is presented for one buyer and one supplier, which results in a near optimal master plan for the SC as a whole.

The joint replenishment inventory control policy analysed by Nielsen and Larsen (2005) can be attributed to a central purchasing function. Dellaert and Jeunet (2005) demonstrate how stockout situations may arise in a deterministic, multi-level, rolling schedule environment and devise a procedure to overcome this problem (see material requirements planning).

Some researchers consider specific SCs, which are not adequately represented in the general architecture of today's APS. The paper of Arbib and Marinelli (2005) is concerned with a line of business where cutting operations are a key issue. A hierarchical production planning system is proposed covering master planning and production planning and detailed scheduling. The integration of production scheduling and shipment planning at oil refineries is the concern of Persson and Göthe-Lundgren (2005). Here, a column generation approach is used for solving the resultant model.

4. The future of advanced planning—issues and challenges

In the following we would like to point out some drawbacks and deficiencies of today's APS and indicate research results and opportunities for their resolution.

The issues and challenges of today's APS will be discussed in three main categories. Firstly, research results are available as well as implementations are under way for improving modules of an APS. The aim is to achieve an even better fit between modules, planning tasks and decision making. Secondly, one may challenge the premises of today's APS, like bucket oriented planning, the consideration of uncertainty by rolling planning and (single-stage) safety stocks or even the applicability of the principles of hierarchical planning for an inter-organizational SC. Thirdly, today's APS are recommended for the seamless integration of business functions. We will argue that there are still missing links between APS and real-time control of the shop floor as well as cost accounting systems.

4.1. Modules

We will start the discussion by looking at ways to improve existing APS modules

4.1.1. Demand planning

Accurate demand forecasts are an important input to decision models used in APS. Forecast errors are directly related to required safety stocks, while frequent adjustments of demand forecasts can lead to dramatic changes in plans (i.e. nervousness). Hence, great emphasis has to be put on choosing correct forecasting models. So far sophisticated models are very rare in *demand planning*. For example consider the behaviour of customers responding to price promotions. Here, the impact of varying sales prices between packages of the same good has to be taken into account when estimating sales (Huchzermeier et al., 2002).

4.1.2. Master planning

Master planning has to coordinate activities and processes along a SC and thus has to capture decisions in procurement, transport, production and distribution adequately. The integration of transport and production decisions within SCs has been the concern of several papers (e.g. Simpson and Erengüc, 2001; Zäpfel and Wasner, 2000; Haehling von Lanzenauer and Pilz-Glombik, 2000). However, these proposals lead to an increased complexity due to additional integer variables for discrete transport amounts.

So far master planning has been devised largely for make- and assemble-to-stock industries while engineer-to-order industries with only a few customers and low volume production quantities (like ship building and aircraft industries) are not adequately represented at the master planning level. Here, elements of a resource-constrained project scheduling type of model are still missing (see the proposals by Kolisch, 2001; Stadtler, 2002b).

In some branches of industry lot-sizing plays a major role (like in the process industry). Consequently, various lot-sizing rules have to be incorporated already at the master planning level (see Wolsey, 2002). While simple minimum lot-size restrictions are already standard, restrictions required for campaign production are currently being implemented. However, there are several situations, which cannot be modelled and solved efficiently today, like long setup times, which extend over a period. One way to overcome this issue is to have production schedules with fixed product cycles (see Mayr, 1996).

In practice one should be very cautious whether all model details mentioned above are really needed at the master planning level. Often a compromise between model detail and solution capabilities of algorithms employed has to be looked for.

4.1.3. Production planning and detailed scheduling

Especially production planning and detailed scheduling have to be adapted to the specific needs and conditions arising at the shop floor. Here, it does not seem wise to find an overall tool adequate for any possible type of production. A systematic classification of production types and the decision support needed has already been described in an early paper by Drexl et al. (1994). A survey of lot-sizing and scheduling has been presented by Drexl and Kimms (1997).

4.1.4. Purchasing and material requirements planning

Purchasing and material requirements planning is often limited to the functionality of the traditional material requirements planning module of an ERP system (Vollman et al., 1997). Recently, there have been proposals to incorporate uncapacitated (Tempelmeier, 2003) as well as capacitated purchasing models including various forms of discount options (Reith-Ahlemeier, 2002).

4.1.5. Demand fulfilment and ATP

So far demand fulfilment and ATP have not attracted many researchers. Fleischmann and Meyr (2003) show how linear and mixed integer programming models can be used for order promising and due date setting. The models' constraints (e.g. downstream capacities) largely depend on the location of the decoupling point within the SC. Downs (2002) reports on a successful implementation of an LP model for order promising in the beef industry. Instead of using CTP quantities, production plans are reoptimised whenever there is a new customer request and a due date has to be quoted.

Obviously, the above list is not exhaustive, but highlights some potential developments in line with the current philosophy of APS. Even more challenging are those enhancements, which question the architecture of APS.

4.2. Lifting the premises of today's advanced planning systems

4.2.1. Event-based planning

In some modules time bucket oriented models prevail (like master planning) and plans are updated on a rolling schedule. Although this scheme is well acknowledged, it might need some refinements to reduce nervousness. More importantly, it seems that a reoptimization from scratch is neither necessary nor advisable. Instead an event-scheduling scheme might be more appropriate, where the given plan is updated whenever new information comes in. New information might be a new customer order, a new purchasing opportunity, a production delay or a point in time where the planning horizon is extended by a further time bucket. This may on the one hand question the fixed time bucket concept in favour of a continuous time axis (see Maravelias and Grossmann, 2003; Rom et al., 2002) and on the other hand ask for a new algorithmic design to "optimise" incremental changes to a given plan (Azevedo and Sousa, 2000). A compromise between a fixed time-bucket and a continuous time axis approach consists of allowing activities to take place across time-bucket borders, e.g. a setup carryover (see Suerie and Stadtler, 2002).

4.2.2. Uncertainty

A second point concerns the consideration of uncertainty. So far only deterministic models are employed, while rolling schedules mainly cater for uncertainty. Also it is possible to generate plans (manually) for different scenarios defined by the user. Furthermore, safety stocks may be considered as minimum stock levels in deterministic models.

However, today safety stock calculations are mainly based on single-stage, single item models (as described in Silver et al., 1998). These calculations are performed within demand planning based on the variance of the forecast errors observed. It is well-known that single-stage safety stock models do not adequately grasp the interdependencies of items within a (multi-stage) SC.

Although there has been much progress in inventory theory (see Minner, 2000 for an overview) models often have stringent assumptions. For example, valuable achievements have been reported for multi-echelon periodic review order-up-to policies (de Kok and Visschers, 1999) now allowing to model a wide range of BOMs. Still, a few structures exist which cannot be handled today (e.g. where there is a raw material to be used in two components which then both are assembled into one end item). Also, it seems that the assumption of a constant (but stochastic) demand rate is in contrast to dynamic (e.g. seasonal) demand observed in many industries. Furthermore, the incorporation of lot-size decisions is still missing. Despite such shortcomings, current developments in this area seem very promising (Wagner, 2002).

Another way to cope with uncertainty is by stochastic programming (Eppen et al., 1989; Sen, 1999). The problem here is an exponential growth of model size, if there are several potential outcomes (scenarios) in each period of a multi-period model. Since most real world deterministic mathematical programming models are already hard to solve, stochastic programming models seem to be out of reach for some time (although promising research is under way on decomposition techniques (Escudero et al., 1999; Berkelaar et al., 2002). Instead of considering all scenarios simultaneously, Santoso et al. (2003) restrict the analysis to a representative subset generated by the sample average approximation scheme. The applicability of this approach is demonstrated by solving two real strategic network design problems.

We would like to add that not only demand uncertainties may exist in a SC but also yield and processing time uncertainties, etc. which may require different ways to counteract. For instance uncertainties in the quantity and timing of replenishment orders of a single item with non-stationary demand are considered by Graves (2003). The authors develop a near optimal heuristic and compare it to a simulation-based optimization procedure known as infinitesimal perturbations analysis (Glasserman and Tayur, 1995).

4.2.3. Decentralization and collaboration

A third assumption to question is the centralistic view of hierarchical planning underlying today's APS. It might be suitable in an intra-organizational SC or a focal inter-organizational SC. However, if partners are reluctant to share their data and to feed it into a central data-base while insisting on their own planning domain, modelling SC-wide flows by a single APS is no longer possible.

For coordinating decentralized plans agent technology has attracted many researchers in recent years (mostly in the area of computer science and artificial intelligence). Software agents are regarded as self interested, autonomous, rational entities having their own objective(s) and being in charge of a certain sub-task of an overall decision problem. For solving their sub-tasks, agents have to communicate and to coordinate their decisions (e.g. consider an agent representing a resource offering available capacity and an agent for a specific order looking for a resource for processing). Coordination requires an extensive exchange of information (e.g. of bids) until a compromise solution is reached. For coordinating decisions several auction mechanisms are available (Fischer et al., 1998).

Applications of agent technology in the area of SCM are reported e.g. by Kjenstad (1998) and Fox et al. (2000). In the latter functional agents are responsible for order acquisition, logistics, transport, or scheduling. They can be used to model a SC and are able to interact in order to plan and execute operations. An overview of various articles on agent-based solutions for production planning and control as well as SCM is given by Grolik et al. (2001).

The ideal environment for agent technology seems to be one with distinct objects to negotiate (like orders in detailed scheduling). At least, in case the objects to coordinate are continuous (like production amounts in master planning) sophisticated decision models seem to be most appropriate together with an intelligent negotiation scheme (see Dudek and Stadtler, this issue).

A related but still difficult to solve problem is the setting of (fair) transfer prices both in an inter-organizational SC (see Pfeiffer, 1999) as well as in a globally operating intra-organizational SC (see Goetschalckx, 2002).

4.3. Seamless integration of business functions

Most software vendors boost their APS for a seamless integration of business functions even across a company's boundaries. Indeed this has been accomplished to a large extent as far as information technology is concerned.

4.3.1. Linking an APS with the shop floor

However, one link is still missing—the link to production control at the shop floor. So far detailed scheduling receives its input data via a transactional ERP system, which is not capable of performing real time control of productions operations. At least for (fully) automated production systems there is a need for a direct link between scheduling and execution. In light of this gap, further software systems have been created—manufacturing execution systems (MES)—which allow an easy to configure link to real time control devices at the shop floor (MESA, 1997). However, MES have a great overlap in functionality with an APS's detailed scheduling. To avoid additional software systems APS should be capable of being linked directly to real time control devices.

4.3.2. Linking an APS with cost accounting

A second issue is the 'correct' input data for decision models. Although technically possible, there is no direct link between an APS and a company's cost accounting system. The reason is that costs calculated in accounting systems serve several purposes, like an ex post evaluation of the profitability of a specific customer order or the total cost of a machine hour, but usually not to become an input to decision models (an early work on this issue is Adam (1970)). Recently, there has been a renewed discussion about the 'correct' inventory holding costs in purchasing models (Fleischmann, 2001). The usual approach is to specify the inventory holding cost per item per period as the interest to be paid on the value of that item. This approach is challenged in case there are different sources of supply for an item at different costs per unit. Since it is not clear which items are withdrawn first—e.g. the cheapest or the most expensive ones—the 'value' of the remaining inventory is no longer clear. One way to overcome this problem is to convert the objective function into minimizing the net present value of cash flows (Helber, 1998). However, assuming that compound interest is negligible, Fleischmann (2001) has shown that cost accounting figures may still result in (the same) correct decisions, if holding costs are not attributed to inventory levels but to the material flows (e.g. purchasing decision variables). This example highlights the need for further research efforts for making use of accounting data within APS.

A favourite means of controlling business activities today is target setting by key performance indicators. This has a long tradition both in industrial practice as well as in theory. Attention has been renewed by the proposal of balanced scorecards (Kaplan and Norton, 1992). Several systems have been advocated for aggregating and disaggregating performance indicators consistently (e.g. Strack and Villis, 2000). It seems that if APS planning results should have an impact on managerial decision-making, it has to be either guided by targets of (key) performance indicators or at least evaluated in these terms ex-post. Note, that a model's outcome, e.g. the maximum contribution of a business unit over a given planning interval, is a performance indicator, but it may not be the only performance indicator a manager has to look at. Hence, there is a greater need to link APS with accounting standards (for an example see Whitehair and Berg, 2002).

5. Concluding remarks

Despite great progress in modelling and solution capabilities there are still many areas for improvements and for future research in SCM and AP. While the issues facing an inter-organizational SC are mainly addressed in research areas associated with the integration of individual organizations, our knowledge regarding process orientation and advanced planning across company borders is still in its infancy (Croom et al., 2000).

As we have pointed out not only the underlying mathematics is concerned but also interdisciplinary research incorporating computer science, accounting and organizational theory, etc.—research efforts which very much parallel the challenges companies face when putting SCM to work. Some of these research questions are addressed in this feature issue.

References

Adam, D., 1970. Entscheidungsorientierte Kostenbewertung, Wiesbaden.

Anthony, R.N., 1965. Planning and Control Systems. A Framework of Analysis, Boston.

Arbib, C., Marinelli, F., 2005. Integrating process optimization and inventory planning in cutting-stock with skiving option: An optimization model and its application. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00057-8.

Azevedo, A.L., Sousa, J.P., 2000. Order planning for networked make-to-order enterprises—a case study. Journal of the Operational Research Society 51, 1116–1127.

Berens, W., Strauch, J., 1999. Herkunft und Inhalt des Begriffes due diligence. In: Berens, W., Brauner, H.U. (Eds.), Due Diligence bei Unternehmensaquisitionen, Stuttgart, pp. 3–20.

Berkelaar, A., Deert, C., Oldenkanp, B., Zhang, S., 2002. A primal-dual decomposition-based interior point approach to two-stage stochastic linear programming. Operations Research 50, 904–915.

Berry, W.L., Hill, T., Klompmaker, J.E., 1999. Aligning marketing and manufacturing strategies with the market. International Journal of Production Research 37, 3599–3618.

Carlsson, D., Rönnqvist, M., 2005. Supply chain management in forestry—case studies at Södra Cell AB. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00061-X.

Childerhouse, P., Aitken, J., Towill, D.R., 2002. Analysis and design of focused demand chains. Journal of Operations Management 20, 675–689.

Christopher, M., 1998. Logistics and Supply Chain Management. Strategies for Reducing Cost and Improving Service. second ed. London.

Corbett, C.J., DeCroix, G.A., Ha, A.J., 2005. Optimal shared savings contracts in supply chains: Linear contracts and double moral hazard. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00046-3.

Croom, S., Romano, P., Giannakis, M., 2000. Supply chain management: An analytical framework for critical literature review. European Journal of Purchasing & Supply Management 6, 67–83.

Dellaert, N., Jeunet, J., 2005. An alternative to safety stock policies for multi-level rolling schedule MRP problems. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00041-4.

de Kok, A.G., Visschers, J.W.C.H., 1999. Analysis of assembly systems with service level constraints. Journal of Production Economics 59, 313–326.

Downs, B., 2002. An LP-based capable-to promise system for beef production at ConGra foods. Paper presented at the INFORMS Annual Meeting at San Jose, CA, November 17–20.

Drexl, A., Fleischmann, B., Günther, H.-O., Stadtler, H., Tempelmeier, H., 1994. Konzeptionelle Grundlagen kapazitätsorientierter PPS-Systeme. Zeitschrift für betriebswirtschaftliche Forschung 46, 1022–1045.

Drexl, A., Kimms, A., 1997. Lotsizing and scheduling—survey and extensions. European Journal of Operational Research 99, 221–235.

Dudek, G., Stadtler, H., 2005. Negotiation-based collaborative planning between supply chains partners. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00024-4.

Eppen, G.D., Martin, R.K., Schrage, L., 1989. A scenario approach to capacity planning. Operations Research 37, 517–527.

Escudero, L.F., Galindo, E., Garcia, G., Gomez, E., Sabau, V., 1999. Schumann, a modeling framework for supply chain management under uncertainty. European Journal of Operational Research 119, 14–34.

Fawcett, S.E., Myers, M.B., 2001. Product and employee development in advanced manufacturing: Implementation and impact. International Journal of Production Research 39, 65–79.

Fischer, K., Ruß, C., Vierke, G., 1998. Decision theory and coordination in multiagent systems. Research Report RR-98-02, Deutsches Forschungszentrum für Künstliche Intelligenz GmbH, Kaiserslautern, Germany.

Fischer, M., 2001. Available-to-promise: Aufgaben und Verfahren im Rahmen des Supply Chain Management, Regensburg.

Fleischmann, B., 2001. On the use and misuse of holding cost models. In: Kischka P., Leopold-Wildenburger, U., Möhring, R.H., Radermacher, F.-J. (Eds.), Models, Methods and Decision Support for Management, Berlin, pp. 147–164.

Fleischmann, B., Meyr, H., 2003. Customer orientation in advanced planning systems. In: Dyckhoff, H., Lackes, R., Reese, J. (Eds.), Supply Chain Management and Reverse Logistics, Berlin, pp. 297–321.

Fox, M.S., Barbuceanu, M., Teigen, R., 2000. Agent oriented supply chain management. International Journal of Flexible Manufacturing Systems 12, 165–188.

Goetschalckx, M., 2002. Strategic network planning. In: Stadtler, H., Kilger, C. (Eds.), Supply Chain Management and Advanced Planning—Concepts, Models Software and Case Studies, Berlin, pp. 105–121.

Glasserman, P., Tayur, S., 1995. Sensitivity analysis for base-stock levels in multiechelon production-inventory systems. Management Science 41, 263–281.

Graves, S.C., 2003. Replenishment planning in discrete-time, capacitated, non-stationary, stochastic inventory systems. Working Paper of Massachusetts Institute of Technology.

Grolik, S., Stockheim, T., Wendt, O., Albayrak, S., Fricke, S., 2001. Dispositive Supply-Web-Koordination durch Multiagentensysteme. Wirtschaftsinformatik 43, 143–155.

Håkansson, H., Johanson, J., 1990. Formal and informal cooperation strategies in international networks. In: Ford, D. (Ed.), Understanding Business Markets, London, pp. 100–111.

Hammer, M., Champy, J., 1993. Reengineering the Corporation, New York.

Hammer, M., 2001. The superefficient company. Harvard Business Review 79, 82–91.

Haehling von Lanzenauer, C., Pilz-Glombik, K., 2000. A supply chain optimization model for MIT's beer distribution game. Zeitschrift für Betriebswirtschaftslehre 70, 101–116.

Hax, A.C., Meal, H.C., 1975. Hierarchical integration of production planning and scheduling. In: Geisler, M.A. (Ed.), Studies in Management Science, vol. I, Logistics, Amsterdam, pp. 53–69.

Helber, S., 1998. Cash flow oriented lot-sizing in MRP II systems. In: Drexl, A., Kimms, A. (Eds.), Beyond Manufacturing Resource Planning (MRP II), Berlin, pp. 147–183.

Huchzermeier, A., Iyer, A., Freiheit, J., 2002. The supply chain impact of smart customers in a promotional environment. Manufacturing & Service Operations Management 4, 228–240.

Kolisch, R., 2001. Make-to-order Assembly Management, Berlin.

Kaplan, R.S., Norton, D.P., 1992. The balanced scorecard—measures that drive performance. Harvard Business Review 70 (1), 72–79.

Kilger, C., Schneeweiss, L., 2002. Demand fulfilment and ATP. In: Stadtler, H., Kilger, C. (Eds.), Supply Chain Management and Advanced Planning—Concepts, Models, Software and Case Studies, Berlin, pp. 161–175.

Kjenstad, D., 1998. Coordinated supply chain scheduling. Ph.D. thesis. Norwegian University of Science and Technology—NTNU. Department of Production and Quality Engineering, Trondheim, Norway.

Lee, H.L., Padmanabhan, V., Wang, S., 1997. The bullwhip effect in supply chains. Sloan Management Review 38 (Spring), 93–102.

Maravelias, C.T., Grossmann, I.E., 2003. New general continuous-time state-task network formulation for short-term scheduling of multipurpose batch plants. Industrial & Engineering Chemistry Research 42 (13), 3056–3074.

Mayr, M., 1996. Hierarchische Produktionsplanung mit zyklischen Auflagemustern, Regensburg.

Meyr, H., Wagner, M., Rohde, J., 2002. Structure of advanced planning systems. In: Stadtler, H., Kilger, C. (Eds.), Supply Chain Management and Advanced Planning—Concepts, Models Software and Case Studies, Berlin, pp. 99–104.

MESA, 1997. MES explained: A high level vision. White paper number 6, September 1997. MESA International.

Minner, S., 2000. Strategic Safety Stocks in Supply Chains. Lecture Notes in Economics and Mathematical Systems 490, Berlin.

Nielsen, C., Larsen, C., 2005. An analytical study of the Q(s,S) policy applied to the joint replenishment problem. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00066-9.

Oliver, R.K., Webber, M.D., 1992. Supply-chain management: Logistics catches up with strategy (reprint from Outlook 1982). In: Christopher, M. (Ed.), Logistics—the Strategic Issues, London, pp. 63–75.

Otto, A., Kotzab, H., 1999. How supply chain management contributes to the management of supply chains—preliminary thoughts on an unpopular question. In: Larsson, E., Paulsson, U. (Eds.), Building New Bridges in Logistics. Lund University, Lund, pp. 213–236.

Persson, J.A., Göthe-Lundgren, M., 2005. Shipment planning at oil refineries using column generation and valid inequalities. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00090-6.

Pfeiffer, T., 1999. Transfer pricing and decentralized dynamic lot-sizing in multistage, multiproduct production processes. European Journal of Operational Research 116, 319–330.

Pfohl, H.-C., Mayer, S., 1999. Insight to Impact, Results of the Fourth Quinquennial European Logistics Study. ELA European Logistics Association/A.T. Kearney, Brussels.

Porter, M.E., 1998. On Competition. A Harvard Business Review Book, Boston, MA.

Reith-Ahlemeier, G., 2002. Ressourcenorientierte Bestellmengenplanung und Lieferantenauswahl. Modelle und Algorithmen für die Supply Chain Optimierung und E-Commerce, Leichlingen.

Ramdas, K., Spekman, R.E., 2000. Chain or shackles: Understanding what drives supply-chain performance. Interfaces 30 (4), 3–21.

Ries, A., 2001. Controlling in virtuellen Netzwerken, Managementunterstützung in dynamischen Kooperationen. Gabler, Wiesbaden.

Robotis, A., Bhattacharya, S., van Wassenhove, L.N., 2005. The effect of remanufacturing on procurement decisions for resellers in secondary markets. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00016-5.

Rom, W.O., Tukel, O.I., Muscatello, J.R., 2002. MRP in a job shop environment using a resource constrained project scheduling model. Omega 30, 275–286.

Santoso, T., Ahmed, S., Goetschalckx, M., 2003. A stochastic programming approach for supply chain network design under uncertainty. Working Paper. School of Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, GA 30332.

Sen, S., 1999. An introductory tutorial on stochastic linear programming models. Interfaces 29, 33–61.

Silver, E.A., Pyke, D.F., Peterson, R., 1998. Inventory Management and Production Planning and Scheduling, third ed. New York.

Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E., 2003. Designing and managing the supply chain. Concepts, strategies, and case studies. second ed., Boston.

Simpson, N.C., Erengüc, S.S., 2001. Modeling the order picking function in supply chain systems: Formulation, experimentation, and insights. IIE Transactions 33, 119–130.

Skinner, W., 1974. The focused factory. Harvard Business Review 52, 113–121.

Skjøtt-Larsen, T., 1999. Interorganisational relations from a supply chain management point of view. Logistik Management 1, 96–108.

Sleptchenko, A., van der Heijdren, M.C., van Harten, A., 2005. Using repair priorities to reduce stock investment in spare part networks. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00062-1.

Spekman, R.E., Forbes III, T.M., Isabella, L.A., MacAvoy, T.C., 1998. Alliance management: A review from the past and a look to the future. Journal of Management Studies 35, 747–772.

Spitter, J.M., Hurkens, C.A.J., de Kok, A.G., Lenstra, J.K., Negenman, E.G., 2005. Linear programming models with planned lead times for supply chain operations planning. European Journal of Operational Research, this issue. doi:10.1016/S0377-2217(04)00040-2.

Stadtler, H., 2002. Basics of supply chain management. In: Stadtler, H., Kilger, C. (Eds.), Supply Chain Management and Advanced Planning—Concepts, Models, Software and Case Studies, Berlin, pp. 7–28.

Stadtler, H., 2002. Multi-level capacitated lot-sizing and resource constrained project scheduling: An integrating perspective. Working Paper. Darmstadt University of Technology (Schriften zur Quantitativen Betriebswirtschaftslehre) 1/2002.

Strack, R., Villis, U., 2000. RAVE™: Die nächste Generation im Shareholder Management. Zeitschrift für Betriebswirtschaft 71, 67–84.

Suerie, C., Stadtler, H., 2002. The capacitated lot-sizing problem with linked lot-sizes. Management Science 49, 1039–1054.

Sydow, J., 1999. Editorial—Über Netzwerke, Allianzsysteme, Verbünde, Kooperationen und Konstellationen. In: Sydow, J. (Ed.), Management von Netzwerkorganisationen, Wiesbaden, pp. 1–6.

Tempelmeier, H., 2003. Material-Logistik. Modelle und Algorithmen für die Produktionsplanung und Steuerung und das Supply Chain Management. fifth ed., Berlin.

Vollman, T.E., Berry, W.L., Whybark, D.C., 1997. Manufacturing Planning and Control Systems. fourth ed., New York.

Wagner, M., 2002. Safety stocks in capacity-constrained production systems. In: Klose, A., Speranza, M.G., van Wassenhove, L.N. (Eds.), Quantitative Approaches to Distribution Logistics and Supply Chain Management, Berlin, pp. 379–393.

Whitehair, R.C., Berg, A.J., 2002. Leveraging knowledge: Solving the problem is no longer enough. Supplement to OR/MS today.

Wildemann, H., 1997. Koordination von Unternehmensnetzwerken. Zeitschrift für Betriebswirtschaft 67, 417–439.

Wolsey, L.A., 2002. Solving multi-item lot-sizing problems with an MIP Solver using classification and reformulation. Management Science 48, 1587–1602.

Zäpfel, G., Wasner, M., 2000. Modellierung von Logistikketten und Möglichkeiten der Optimierung, gezeigt an einem Praxisfall der Stahllogistik. Zeitschrift für Betriebswirtschaft 70, 267–288.