Chapter 2
Supply Chain Planning and Coordination

The aim of this chapter is to familiarize the reader with the topic of this work, how to coordinate mid-term planning in *decentralized* supply chains, i.e., supply chains that comprise several independent, legally separated parties with their own decision authorities. We start with a description of planning in *centralized* supply chains (Sect. 2.1), where the decision authority and the knowledge of all relevant planning data is hold by a single party. In Sect. 2.2 we provide centralized mathematical model formulations for mid-term supply chain planning (Master Planning). Section 2.3 deals with supply chain planning in decentralized environments. We describe the differences in the planning processes compared to centralized planning, provide reasons for the potential suboptimality of decentralized planning and introduce coordination and, more specifically, collaborative planning as approaches to mitigate this suboptimality.

2.1 Supply Chain Planning

2.1.1 Definitions and Overview

We begin with an abstract and often cited definition of a supply chain: A supply chain 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 hands of the ultimate consumer."[1] As an illustration, we depict in Fig. 2.1 a supply chain consisting of a set of vendors, plants, distribution centers, and customers that are linked by material flows.[2]

From a business economics perspective, supply chains require supply chain management, that can be defined as "the task of integrating organizational units along a supply chain and coordinating material, information and financial flows in order to fulfill (ultimate) customer demands with the aim of improving the

[1] Christopher (2005, p. 17).

[2] For similar representations, see, e.g., Shapiro (2001, p. 6) and Stadtler (2007b, p. 10).

M. Albrecht, *Supply Chain Coordination Mechanisms: New Approaches for Collaborative Planning*, Lecture Notes in Economics and Mathematical Systems 628,
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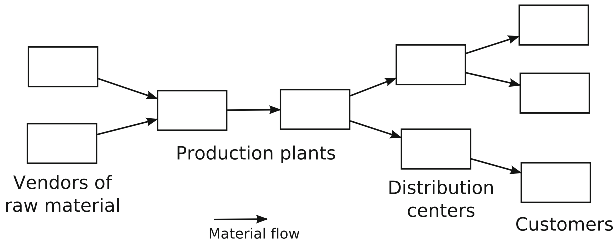

Fig. 2.1 Sketch of a supply chain (example)

competitiveness of a supply chain as a whole."[3] One of the building blocks of supply chain management is (advanced) supply chain planning.[4] The aim of supply chain planning is to determine an integrated plan for the whole supply chain; referring to Fig. 2.1, such a plan comprises appropriate quantities of the raw materials procured, of the products manufactured in the plants, of the products distributed, and of the products sold to the customers.

Of course, this is a very complex task especially for real-world organizations, which may comprise a large number of facilities, customers, and products. Therefore, it has been proposed in the literature[5] to organize (production) planning in a *hierarchical* way.[6] The basic idea of hierarchical planning is the separation of decisions according to their impact, e.g., on the profitability of the supply chain. The decisions at the upper levels, i.e., those with greater impact, are determined first and implemented as targets for the planning of the lower levels. Further important characteristics are the aggregation of data and decisions at the upper levels and the provision of feedback by the lower levels.[7]

A common representation for the individual tasks of supply chain planning is the Supply Chain Planning Matrix (see Fig. 2.2).[8] Frequently, these planning tasks are supported by software tools in practice. As a standard software, Advanced Planning Systems (APS) have been developed by different companies (e.g., SAP, Oracle[9]). Each APS contains several modules that cover in part the planning tasks stated in Fig. 2.2. The Advanced Planning Matrix provides an overview of these modules (see Fig. 2.3).[10] Long-term planning is the object of Strategic

[3] Stadtler (2007b, p. 11).

[4] See Stadtler (2007b, p. 27).

[5] See, Hax and Meal (1975, p. 53) and the work of Stadtler (1988) as a comprehensive introduction into hierarchical planning.

[6] Although originally proposed for production planning, this concept equally applies to planning in supply chains.

[7] See, e.g., Stadtler (2007b, p. 32).

[8] See Fleischmann et al. (2007, p. 102).

[9] See SAP (2008) and Oracle (2008). The market share of APS is substantial and steadily growing; e.g., in 2005, revenues increased by $40 million up to $741 million, see White et al. (2006, p. 2).

[10] Figure 2.3 has been adapted from Meyr et al. (2007b, p. 109) with slight modifications (see below).

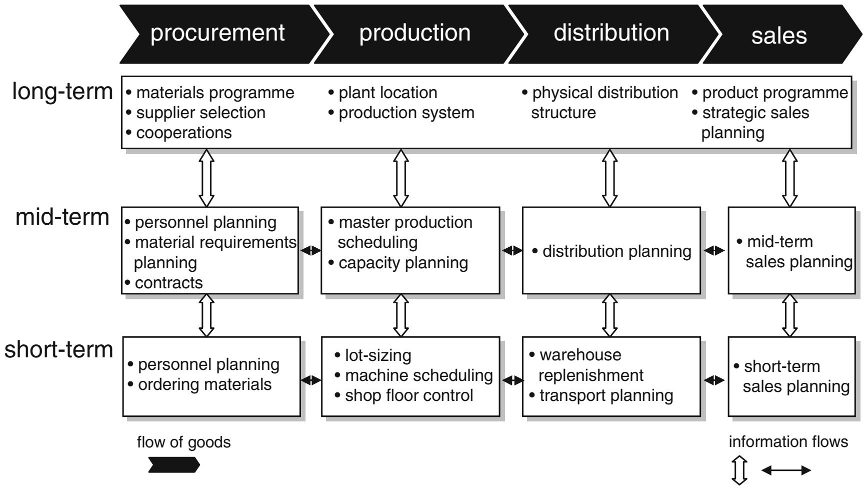

Fig. 2.2 Supply Chain Planning Matrix

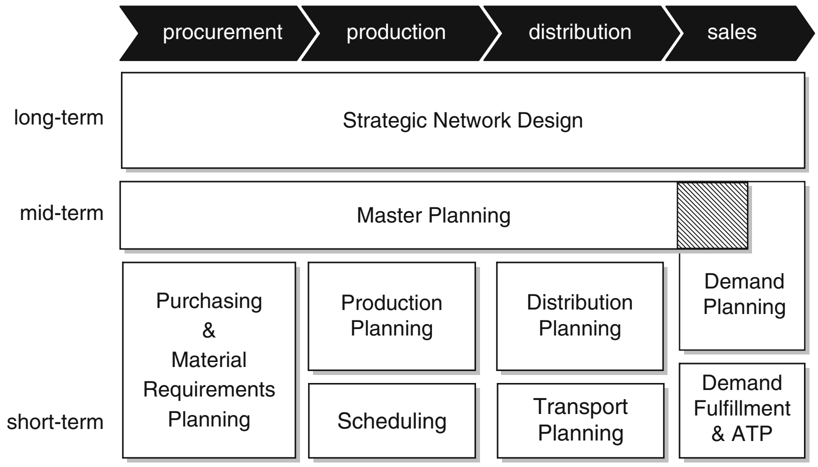

Fig. 2.3 Advanced Planning Matrix

Network Design, whereas the mid-term planning tasks are covered by Purchasing & Material Requirements Planning, Master Planning, Production Planning, Distribution Planning, and Demand Planning. Analogously, the short-term planning tasks are tackled by Purchasing & Material Requirements Planning, Production Planning, Scheduling, Transport Planning, Demand Fulfillment & Available-To-Promise (ATP). Note that Fig. 2.3 differs from the original Advanced Planning Matrix by the overlap of Master Planning into sales (see the shadowed area in Fig. 2.3). In our opinion, this is more concise than the original representation since Master Planning frequently involves sales-related decisions like backorders and lost sales.[11]

In the following, we will provide a more detailed description of Master Planning, which is the main focus of this work. For an in-depth explanation of the other modules, we refer to the textbook of Stadtler and Kilger (2007).[12]

2.1.2 Master Planning

Master Planning means mid-term operational decision-making carried out simultaneously for all functional areas participating in the order fulfillment process: Procurement, production, distribution, and sales. In this work, we focus on this planning level since the potential financial impact for collaborating enterprises is largest here.

Master Planning is based on monthly or weekly time buckets; hence, planning horizons of, e.g., 12, 24, or 52 periods are used. It is important that the planning horizon is chosen such large that effects due to seasonal demand are considered. This requires that the planning interval comprises one seasonal cycle at least.

Table 2.1 provides an overview about the basic decisions made within Master Planning. Most of these decisions are likewise mentioned in other descriptions of Master Planning.[13] A somewhat ambiguous role in this context plays lot-sizing,

Table 2.1 Basic decisions of Master Planning

Functional area	Decision
Procurement	Quantities of raw materials to purchase
Production	Production quantities
	Resource utilization
	Inventory levels
	Utilization of overtime
	Lot-sizing
Distribution	Quantities of products to transport
	Inventory levels
Sales	Quantities of products to deliver to the customers (including backorders and lost sales)

[11] See also Sect. 2.1.2. The importance of (lost) sales for integrated mid-term planning is further supported by the practitioner-oriented literature, where mid-term planning models with the aim of profit maximization have been proposed, see, e.g., Timpe and Kallrath (2001, p. 423) and Kallrath (2002, p. 315) for a model that additionally includes strategic aspects.

[12] See Stadtler and Kilger (2007, p. 117).

[13] See Rohde and Wagner (2007, p. 160) and Günther (2006, p. 20).

which is often regarded as a short-term planning task in the literature.[14] Indeed, lot-sizing is not an issue for mid-term planning in many industries.[15] A noteworthy exception, however, are process industries, where lot-sizing decisions have a substantial impact on the quality of the resulting plans. Due to large setup times and expensive setup activities, practical mid-term planning model formulations originating from this area usually include lot-sizing.[16]

The results of these decisions (e.g., the planned amount of stock or the planned use of overtime[17]) constitute targets for the lower-level modules Purchasing & Material Requirements Planning, Production Planning, and Distribution Planning. Note that, according to the principles of hierarchical planning, the corresponding data has to be disaggregated for this purpose.

The input data for Master Planning is deterministic. Real-world data, especially demand forecasts, however, always comprise some uncertainty. Because of that, mid-term planning models incorporating stochastic data have been elaborated in the literature.[18] In practice, however, stochastic decision models are rarely used for mid-term planning. Instead, planning is done based on *rolling schedules*.[19] This means that only the first periods of plans (i.e., the periods before the frozen horizon) are implemented; the rest is determined later by re-planning, which is undertaken periodically (e.g., once a month). This approach provides the flexibility to react with plan changes if uncertainty is revealed in future periods.

2.2 Model Formulations for Master Planning

In this section, we present mathematical model formulations for Master Planning that are used throughout this work (among others, for the computational verification of the coordination schemes proposed). First of all, we provide a generic linear programming (LP) model in Sect. 2.2.1. Compared to mixed-integer programming (MIP) or nonlinear programming (NLP), the mathematical structure of LP is much simpler, which makes approaches based on LP particularly suited for structural analyses. However, results valid for LP do not necessarily extend to other model classes.[20] These classes include MIP models, which are required for modeling

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[14] As an example, see the Supply Chain Planning Matrix on p. 7 of this work.

[15] This holds, e.g., for the (German) automotive industry, see Meyr (2004, p. 447).

[16] E.g., Timpe and Kallrath (2001, p. 42) and Grunow et al. (2003, p. 109).

[17] See, e.g., Rohde and Wagner (2007, p. 161).

[18] E.g., Leung et al. (2007, p. 2282), Escudero et al. (1993, p. 311), and Scholl (2001, p. 295).

[19] See, e.g., Fleischmann et al. (2007, p. 84).

[20] As an example, consider the simplex algorithm, a common solution procedure for LP models, which yields the optimal solution to, e.g., MIP models only in case of the total unimodularity of the underlying matrix of coefficients, see Domschke and Drexl (2006, p. 91); for a description of the simplex algorithm and of solution procedures for MIP models such as branch and bound, see, e.g., Domschke and Drexl (2006, p. 21 and p. 126).

lot-sizing decisions at the Master Planning level. Therefore, we additionally provide model formulations accounting for lot-sizing in Sect. 2.2.2.[21]

2.2.1 Generic Master Planning Model

Before presenting the mathematical formulation of the generic Master Planning model (GM), we state its underlying assumptions:

- Several items are arranged in a general bill of material (BOM) and produced on one or more specific resources. Production results in variable capacity loads.
- The capacities of the resources are finite and can be extended by costly, infinitely available overtime.
- Demand is dynamic and deterministic for all items.
- Unfulfilled demand can either be backlogged or lost; both actions incur additional costs.
- Inventory holding of items is possible and results in holding costs.

$$\min \sum_{j\in J}\sum_{t\in T} h_j I_{jt} + \sum_{m\in M}\sum_{t\in T} oc_m O_{mt} + \sum_{j\in J^E}\sum_{t\in T}\left(blc_j BL_{jt} + lsc_j LS_{jt}\right)$$

$$\text{s.t. } BL_{jt} + LS_{jt} + I_{jt-1} + X_{jt} = d_{jt} + BL_{jt-1} + I_{jt} \quad \forall j \in J^E, t \in T \tag{2.1}$$

(GM)

$$I_{jt-1} + X_{jt} = \sum_{k\in S_j} r_{jk} X_{kt} + I_{jt} \quad \forall j \in J \setminus J^E, t \in T \tag{2.2}$$

$$\sum_{j\in J} a_{mj} X_{jt} \le k_{mt} + O_{mt} \quad \forall m \in M, t \in T \tag{2.3}$$

$$BL_{j0} = bl_j^0 \quad \forall j \in J^E \tag{2.4}$$

$$BL_{j|T|} = bl_j^T \quad \forall j \in J^E \tag{2.5}$$

$$I_{j0} = i_j^0 \quad \forall j \in J \tag{2.6}$$

$$BL_{jt} \ge 0 \quad \forall j \in J^E, t \in T \cup \{0\} \tag{2.7}$$

$$I_{jt} \ge 0 \quad \forall j \in J, t \in T \cup \{0\} \tag{2.8}$$

$$LS_{jt} \ge 0 \quad \forall j \in J^E, t \in T \tag{2.9}$$

$$O_{mt} \ge 0 \quad \forall m \in M, t \in T \tag{2.10}$$

$$X_{jt} \ge 0 \quad \forall j \in J, t \in T. \tag{2.11}$$

[21] Note that there are further decisions and restrictions in Master Planning that rely on MIP for their modeling. An example is the restriction that overtime can only be taken in an integer number of shifts, which is used in our computational tests of Sect. 6.1 for analyzing the sensitivity of the scheme regarding the presence of integer variables.

Indices and Index Sets

j Items or operations (e.g., end products, intermediate products, raw materials), $j \in J$; J^E is the subset of (end) items sold to external customers

m Resources (e.g., personnel, machines, production lines), $m \in M$

t Periods, $t \in T$, with $T = 1, \ldots, |T|$

S_j Set of immediate successors of item j in the BOM

Data

a_{mj} Capacity needed on resource m for one unit of item j

blc_j Backorder costs for one unit of item j in a period

bl_j^0 Amount of backorders for item j at the beginning of the planning interval

bl_j^T Amount of backorders for item j at the end of the planning interval

d_{jt} Primary, gross demand for item j in period t

i_j^0 Inventory of item j at the beginning of the planning interval

h_j Holding costs for one unit of item j in a period

k_{mt} Available capacity of resource m in period t

lsc_j Costs for lost sales of one unit of item j in a period

oc_m Overtime costs for one unit of resource m

r_{jk} Number of units of item j required to produce one unit of the immediate successor item k

Variables

BL_{jt} Amount of backorders for item j in period t

I_{jt} Inventory of item j at the end of period t

LS_{jt} Amount of lost sales of item j in period t

O_{mt} Amount of overtime on resource m in period t

X_{jt} Production amount of item j in period t

The objective function minimizes the costs for inventory holding, overtime, backorders, and lost sales. Constraints (2.1) determine the quantities of the external demand that are backlogged and lost. Constraints (2.2) ensure the fulfillment of the secondary demand.[22] Constraints (2.3) limit the capacity used for production to the sum of normal capacity and overtime. Constraints (2.4)–(2.6) fix the amounts of backorders and inventories at the borders of the planning interval.[23] Finally, (2.7)–(2.11) determine the nonnegativity of the decision variables.

Note that due to its generic character, this model formulation does not cover all decisions potentially relevant for Master Planning.[24] For lot-sizing, we refer to

[22] For ease of exposition, we have separated items into two groups: End items with external demand (J^E) and intermediate items used for production ($J \setminus J^E$). In a setting where an item is used for production and has external demand, this model formulation would have to be adapted accordingly.

[23] This fixation seems the most straightforward possibility for the modeling of backorders. Note that when planning is based on rolling schedules, the modeling of maximum latenesses may be more adequate.

[24] I.e., those listed in Table 2.1 (see p. 8).

the following subsection. Moreover, an exemplary modeling of storage capacities and transportation is included in the model for the real-world planning problems presented in Sect. 6.5.

2.2.2 Extension to Lot-Sizing

A broad variety of models incorporating lot-sizing decisions has been proposed in the literature. We begin with some basic formulations and discuss how to integrate them into Master Planning. Built on this, we present a Master Planning model that is extended to production campaigns. Campaign planning is a variant of lot-sizing with practical relevance for process industries and additional difficulties for supply chain coordination,[25] which makes this extension particularly suited for examining the performance of the coordination schemes proposed in this work.

2.2.2.1 Basic Models

One of the first production planning problems analyzed in the literature is the determination of the economic order quantity (EOQ),[26] i.e., the optimal order quantity of an item based on a number of restrictive assumptions. The most important assumptions are:[27]

- One single item is considered.
- Demand is deterministic and constant.
- The replenishment lead time is zero.
- Inventory holding is possible and results in holding costs.
- Each replenishment requires fixed ordering costs.

Then the total relevant costs per unit time can be expressed by

$$c(Q) = \frac{sc\,d}{Q} + \frac{hQ}{2}.$$

Data

d Demand per unit time

h Unit holding cost per unit time

sc Cost for one replenishment order (= setup cost)

Variables

Q Order quantity

[25] See Example 2.6 as an illustration of this issue.

[26] See Harris (1913, p. 135).

[27] For alternative listings of assumptions underlying the EOQ model, see, e.g., Neumann (1996, p. 28) and Silver et al. (1998, p. 150).

$c(Q)$ is a convex function. It takes its minimum with the EOQ $Q^* = \sqrt{2sc\, d/h}$. Due to the restrictive assumptions, direct applications of this model are rather rare in practice.[28] In spite of that, this model has proved useful as a basis for analyzing lot-sizing decisions in broader contexts, which include the potential cost impact of deviations of lot sizes from the EOQ[29] and supply chain coordination mechanisms.[30]

The term *lot-sizing* also means the determination of optimal order quantities, but – in contrast to the EOQ – without the limitation to constant demand.[31] The most basic lot-sizing model is the uncapacitated dynamic single-item lot-sizing model developed by Wagner and Within (1958).[32] Since the applicability of this model is again rather limited, we state a more relevant extension to several items and several levels of the BOM, the MLULSP (= Multi-Level Uncapacitated Lot-Sizing Problem).[33]

$$\min \sum_{j\in J}\sum_{t\in T} h_j I_{jt} + \sum_{j\in J}\sum_{t\in T} sc_j Y_{jt} \tag{2.12}$$

s.t. (2.2), (2.6), (2.8), (2.11)

(MLULSP)

$$I_{jt-1} + X_{jt} = d_{jt} + I_{jt} \quad \forall j \in J^E, t \in T \tag{2.13}$$

$$X_{jt} \le b_{jt} Y_{jt} \quad \forall j \in J, t \in T \tag{2.14}$$

$$Y_{jt} \in \{0,1\} \quad \forall j \in J, t \in T. \tag{2.15}$$

Data

b_{jt} Large number, not limiting feasible lot size of item j in period t, e.g., $b_{jt} = \sum_{\tau=t}^{|T|} d_{j\tau}$ for $j \in J^E$; for $j \in J \setminus J^E$, b_{jt} can be calculated recursively by $b_{jt} = \sum_{k\in S_j} r_{jk} b_{kt}$

h_j Holding cost for one unit of item j in a period

sc_j Setup cost for a lot of item j

Variables

Y_{jt} Binary setup variable (= 1, if item j is produced in period t, = 0 otherwise)

The objective function (2.12) minimizes the sum of inventory holding and setup costs. Constraints (2.2), (2.6), (2.8), and (2.11) are taken from GM. Constraints (2.13) ensure together with (2.2) the fulfillment of external and secondary demand, respectively. Setup constraints (2.14) enforce variables Y_{jt} to 1 if a lot of item j is produced in period t. Constraints (2.15) define variables Y_{jt} as binary.

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[28] Note that this only holds for this model in its pure form presented above. For some extensions (e.g., to a multi-level BOM), real-world applications have been reported, see, e.g., Muckstadt and Roundy (1993, p. 61) for an automotive manufacturer and Stadtler (1992, p. 217) for a light alloy foundry.

[29] See, e.g., Zangwill (1987, p. 1209) and Stadtler (2007a, p. 407).

[30] See Chap. 3 for examples.

[31] See, e.g., Silver et al. (1998, p. 198). Note that the optimal quantities for single orders usually differ from each other in case of dynamic demand.

[32] See Wagner and Within (1958, p. 89).

[33] See, e.g., Domschke et al. (1997, p. 154).

Combining the MLULSP and GM, we obtain a Multi-Level Capacitated Lot-Sizing Problem (MLCLSP) with backorders and lost sales as a generic Master Planning model that includes decisions related to lot-sizing. This model differs from the original MLCLSP developed by Billington et al. (1983)[34] by the negligence of penalties for undertime and by the inclusion of backorders and lost sales.

$$\min \; C_{\text{MLCLSP}} = \sum_{j \in J} \sum_{t \in T} h_j I_{jt} + \sum_{j \in J} \sum_{t \in T} sc_j Y_{jt} +$$

$$\text{(MLCLSP)} \quad \sum_{m \in M} \sum_{t \in T} oc_m O_{mt} + \sum_{j \in J^E} \sum_{t \in T} blc_j BL_{jt} + \sum_{j \in J^E} \sum_{t \in T} lsc_j LS_{jt}$$

s.t. (2.1)–(2.11), (2.14), (2.15).

Variables

C_{MLCLSP} Value of the objective function of the MLCLSP

2.2.2.2 Extension to Campaign Planning

Campaign planning is a variant of lot-sizing, which raises additional challenges for an efficient mathematical modeling and is of great importance in process industries.[35] Analogously to a production lot, a campaign means the production of several units of items without performing any additional setup operation.[36] The sizes of these units usually cannot be chosen continuously; due to technical restrictions, e.g., fixed tank or reaction volumes, whole *batches*, i.e., prespecified amounts of items, have to be produced. Hence, a campaign length corresponds to an integer number of batch sizes.[37]

For the modeling of campaign planning, the MLCLSP has to be altered in two respects. First, of course, we have to assure that only complete batches are produced. Second, the MLCLSP contains a representation defect, which affects the applicability of this model for campaign planning. The MLCLSP comprises the restrictive assumption that, whenever an item is produced in a period, a setup has to be performed for this item. The setup is required irrespectively whether the resource has already been set up for this item at the end of the preceding period, i.e., the setup state could have been preserved. This representation defect can affect the optimality of the resulting production plans in general.[38] For campaign planning, this effect is significantly aggravated, particularly if the production of a single batch requires a considerable share of the available capacity.

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[34] See Billington et al. (1983, p. 6).

[35] For real-world applications and case studies for campaign planning in process industries, see, e.g., Brandenburg and Tölle (2008), Grunow et al. (2002, p. 281), and Rajaram and Karmarkar (2004, p. 253).

[36] See, e.g., Suerie (2005c, p. 2).

[37] See Kallrath (2005, p. 341).

[38] For an extensive discussion of this issue, see Suerie (2005c, p. 34).

Table 2.2 Comparison of lot-sizing models with the preservation of setup states

	DLSP	CSLP	PLSP	CLSPL	GLSP
Maximum number of items per period	1	1	≤ 2	Arbitrary	Arbitrary
Sequence-dependent setups allowed?	No	No	No	No	Yes

In the literature, several model formulations have been developed that overcome the above mentioned representation defect by allowing lot sizes that overlap period boundaries.[39] These models differ by their scope and their computational complexity. Table 2.2 provides a comparison of five basic models with this property, the DLSP (Discrete Lot-sizing and Scheduling Problem),[40] the CSLP (Continuous Setup Lot-sizing Problem),[41] the PLSP (Proportional Lot-sizing and Scheduling Problem),[42] the GLSP (General Lot-sizing and Scheduling Problem),[43] and the CLSPL (Capacitated Lot-Sizing Problem with Linked lot sizes).[44]

The scopes of these models differ by the maximum number of items that can be produced per time period[45] and by the question whether sequence-dependent setups can be modeled.[46] We choose the CLSPL as the basis for evaluating the coordination schemes proposed. The main reason for this is that the CLSPL allows the production of an arbitrary number of items per period. In anticipation to Sect. 2.3, we want to point out that coordination becomes most relevant if several items are ordered and if decentralized parties have little leeway for adapting their production plans (e.g., due to tight capacities and elevated costs for shortages). In such situation, parties would hardly confine themselves to models which artificially restrict the production to one or two items per period. Potential modest increases in inventory holding and setup costs with the CLSPL are of secondary relevance then. Such increases may be caused by the greater computational complexity of the CLSPL, which usually results in larger optimality gaps compared to the DLSP, CSLP, and PLSP, provided that a limit on the solution time is applied.[47] Sequence-dependent setups, in turn,

[39] For comprehensive surveys of these models see, e.g., Drexl and Kimms (1997, p. 221) and Jans and Degraeve (2008, p. 1619).

[40] See Fleischmann (1990, p. 338).

[41] See Karmarkar and Schrage (1985, p. 328).

[42] See Drexl and Haase (1995, p. 75).

[43] See Fleischmann and Meyr (1997, p. 12).

[44] See Dillenberger et al. (1993, p. 112). More recently, this model has been investigated by Gopalakrishnan et al. (2001, p. 851) and Suerie and Stadtler (2003, p. 1039).

[45] Note that this classification – although sufficient for our subsequent argumentation – is too rough to capture the difference between the DLSP and the CSLP, which is the all-or-nothing condition required by the DLSP and relaxed in the CSLP.

[46] Note that we state here whether the basic formulations of these models (which have been reported in Drexl and Kimms (1997, p. 221) and (Suerie, 2005a, p. 16)) include sequence-dependent setups. This does not always apply to the model type in general; e.g., Fleischmann (1994, p. 397) proposes a variant of the DLSP which allows sequence-dependent setups.

[47] See Suerie (2005c, p. 164) for computational results for campaign planning models based on the PLSP and the CLSPL. Regarding the best solutions found, however, the CLSPL can outperform

are usually not included at the Master Planning level;[48] hence, there is no need for a computationally more demanding model like the GLSP that additionally covers this issue.

Concerning the restrictions on feasible campaigns, we limit here to single-item campaigns with fixed batch sizes.[49] For sake of simplicity, we neither include minimum campaign lengths[50] nor batch availability.[51]

Further discussion deserves the modeling of lead times in the multi-level version of the CLSPL considered here. Lead times of zero, which have implicitly been assumed for the MLCLSP, may cause infeasibility of solutions obtained by multi-level lot-sizing models with the preservation of the setup states. Such infeasibility may arise if a successor item is not produced at the end of a period (i.e., its setup state is not carried over into the next period) and one of its predecessor items is produced at the end of the same period (i.e., its setup state is carried over into the next period). With insufficient inventories of the predecessor item at the beginning of the period, the secondary demand of the successor item might not be fulfilled in time.[52] In order to exclude the generation of infeasible solutions, we choose in analogy to Kimms (1996)[53] lead times equal to or greater than one period length for intermediate items.[54]

Below we present the adaptation of the MLCLSP to the preservation of setup states and campaign restrictions. This model extends the single-level formulation proposed by Suerie (2005b)[55] to a multi-level BOM structure.

$$\min \; C_{\text{MLCLSP}}$$

(MLCLSPL-C) s.t. (2.4)–(2.11), (2.15)

$$LS_{jt} + BL_{jt} + I_{jt-1} + X^b_{jt} + X^e_{jt} = d_{jt} + BL_{jt-1} + I_{jt} \quad \forall j \in J^E, t \in T \tag{2.16}$$

the PLSP (without campaign restrictions) in spite of the larger optimality gaps, see Suerie (2005c, p. 157).

[48] This holds, e.g., for Timpe and Kallrath (2001) and Grunow et al. (2003), the papers cited in Sect. 2.1.2 as examples for lot-sizing decisions in Master Planning.

[49] The modeling of these campaigns in lot-sizing has been introduced by Kallrath (1999, p. 330) and further been improved by Suerie (2005a, p. 49).

[50] For their modeling, see, e.g., Suerie (2005c, p. 95).

[51] For the modeling of batch availability, see, e.g., Brüggemann and Jahnke (1994, p. 755) for the DLSP and Suerie (2005c, p. 98) for the CLSPL.

[52] Note that this problem is only relevant for models with the preservation of setup states and, hence, does not apply to the MLCLSP.

[53] See the formulation of the Multi-Level Proportional Lot-sizing and Scheduling Problem (MLPLSP) in Kimms (1996, p. 87).

[54] This modeling is only exact if exogenous lead times of this duration occur. For single-machine problems, Stadtler (2008) has proposed an extension of the MLPLSP, which allows the modeling of zero lead times. For multi-machine problems (like the problem considered here), however, we are not aware of any corresponding practicable formulation.

[55] Suerie (2005b, p. 102).

$$I_{jt-1} + i_{jt}^{prev} = \sum_{k \in S_j} r_{jk} \left(X_{kt}^b + X_{kt}^e \right) + I_{jt}$$
$$\forall j \in J \setminus J^E, t = 1, \ldots, \tau_j \tag{2.17}$$

$$I_{jt-1} + X_{jt-\tau_j}^b + X_{jt-\tau_j}^e = \sum_{k \in S_j} r_{jk} \left(X_{kt}^b + X_{kt}^e \right) + I_{jt}$$
$$\forall j \in J \setminus J^E, t = \tau_j + 1, \ldots, |T| \tag{2.18}$$

$$\sum_{j \in J} a_{mj} \left(X_{jt}^b + X_{jt}^e \right) + \sum_{\substack{j \in J \\ a_{mj} > 0}} st_j Y_{jt} \leq k_{mt} + O_{mt} \quad \forall m \in M, t \in T \tag{2.19}$$

$$X_{jt}^e \leq b_{jt} Y_{jt} \quad \forall j \in J, t \in T \tag{2.20}$$

$$X_{jt}^b \leq b_{jt} W_{jt-1} \quad \forall j \in J, t \in T \tag{2.21}$$

$$W_{jt} \leq Y_{jt} + W_{jt-1} \quad \forall j \in J, t \in T \setminus \{|T|\} \tag{2.22}$$

$$\sum_{\substack{j \in J \\ a_{mj} > 0}} W_{jt} \leq 1 \quad \forall m \in M, t \in T \setminus \{|T|\} \tag{2.23}$$

$$W_{jt-1} + W_{jt} - Y_{jt} + Y_{kt} \leq 2 \quad \forall m \in M, j, k \in J, k \neq j,$$
$$a_{mj}, a_{mk} > 0, t \in T \setminus \{|T|\} \tag{2.24}$$

$$CAM_{jt} \leq CAM_{jt-1} + X_{jt}^b + b_{jt} Y_{jt} \quad \forall j \in J, t \in T \tag{2.25}$$

$$CAM_{jt} \geq CAM_{jt-1} + X_{jt}^b - b_{jt} Y_{jt} \quad \forall j \in J, t \in T \tag{2.26}$$

$$CAM_{j0} \leq cam_j^0 \quad \forall j \in J \tag{2.27}$$

$$CAM_{jt} \leq X_{jt}^e + b_{jt} \left(1 - Y_{jt} \right) \quad \forall j \in J, t \in T \tag{2.28}$$

$$CAM_{jt} \geq X_{jt}^e \quad \forall j \in J, t \in T \tag{2.29}$$

$$CAM_{jt-1} + X_{jt}^b \geq bs_j YI_{mt} \quad \forall m \in M, j \in J, a_{mj} > 0, t \in T \tag{2.30}$$

$$CAM_{jt-1} + X_{jt}^b = bs_j R_{jt} + S_{jt} \quad \forall j \in J, t \in T \setminus \{1\} \tag{2.31}$$

$$S_{jt} \leq bs_j \left(1 - YI_{mt} \right) \quad \forall m \in M, j \in J, a_{mj} > 0, t \in T \setminus \{1\} \tag{2.32}$$

$$YI_{mt} \geq Y_{jt} \quad \forall m \in M, j \in J, a_{mj} > 0, t \in T \tag{2.33}$$

$$YI_{mt} \leq \sum_{\substack{j \in J \\ a_{mj} > 0}} Y_{jt} \quad \forall m \in M, t \in T \tag{2.34}$$

$$W_{j0} = w_j^0 \quad \forall j \in J \tag{2.35}$$

$$CAM_{jt} \geq 0 \ \forall j \in J, t \in T \cup \{0\} \tag{2.36}$$

$$R_{jt} \in \mathbb{N}_0 \quad \forall j \in J, t \in T \tag{2.37}$$

$$W_{jt} \in \{0, 1\} \quad \forall j \in J, t \in T \setminus \{T\} \tag{2.38}$$

$$S_{jt} \geq 0 \quad \forall j \in J, t \in T \setminus \{1\} \tag{2.39}$$

$$YI_{mt} \geq 0 \quad \forall m \in M, t \in T. \tag{2.40}$$

Data

bs_j Batch size for item j
cam_j^0 Initial campaign quantity for item j
i_{jt}^{prev} Inflow of item j in period t originating from production in earlier periods
st_j Setup time for item j
τ_j Lead time for item j
w_j^0 Initial setup state of item j

Variables

CAM_{jt} Campaign variable for item j in period t (quantity of the current campaign up to period t)
R_{jt} Integer number of full batches produced in the current campaign of item j up to period t
S_{jt} Quantity of the last batch of item j in period t which is not finished in t
W_{jt} Setup state indicator variable ($= 1$ if item j is set up at the end of period t, $= 0$ otherwise)
X_{jt}^b Production quantity of item j at the beginning of period t (i.e., of the first campaign in t)
X_{jt}^e Production quantity of item j that is not produced at the beginning of period t (i.e., not part of the first campaign in t)
YI_{mt} Setup operation indicator for resource m in period t ($= 1$ if a setup occurs on resource m in period t, $= 0$ otherwise)

The objective function and some constraints are taken from the MLCLSP. The inventory balance constraints (2.16)–(2.18) now account for nonzero production lead times.[56] In the left-hand side of constraints (2.16), inflows i_{jt}^{prev} from earlier production periods have been considered, which are relevant if the MLCLSPL-C is applied with rolling schedules. As a prerequisite for modeling production campaigns, we have replaced X_{jt}, the standard variables denoting the production quantities, by X_{jt}^b and X_{jt}^e in (2.16)–(2.18). The same change has been applied to constraints (2.19), where setup times have additionally been included.[57]

The aim of constraints (2.20)–(2.24) is to ensure that in case of production of item j in period t the corresponding resource has been set up for j. Constraints (2.20) force variables Y_{jt} to 1 if item j is produced in period t, but not at the beginning of t.[58] The alternative to a setup operation is a setup carry-over from the preceding period. With a setup carry-over for item j, i.e., $W_{jt-1} = 1$, the production of j can

[56] Note that we have omitted inventory holding of items during their production lead times. The only relevant effect of these inventories is on the relative profitability of items. This, however, can be easily considered by altering the unit penalty costs for lost sales accordingly.

[57] Note that for the validness of these constraints, we implicitly assume that setup times for an item j on a machine m only incur with nonzero variable capacity load for the production of j on m.

[58] Note that in order to avoid infeasibilities, the maximum lot size b_j has to exceed the batch size bs_{jt}.

take place at the beginning of period t [see constraints (2.21)]. Constraints (2.22)–(2.24) ensure correct values for W_{jt}. According to constraints (2.22), W_{jt} can only take 1 if a setup for item j has been performed in period t or if the corresponding resource has already been set up for j at the end of $t-1$. Moreover, each resource can be set up at most for one item at period boundaries [see constraints (2.23)].[59] Finally, we have to exclude a positive setup state for item j both at the beginning and the end of a period if another item k is produced in this period and no setup has been performed for j [see (2.24)].

The properties of feasible campaigns are defined by constraints (2.25)–(2.32). For that purpose, we have introduced variables CAM_{jt} indicating the quantity of the campaign of item j that is finished in the period where, relative to t, the last setup has been performed for j (i.e., in one of the periods $t,\ t-1,\ \dots$).[60] Constraints (2.25) and (2.26) fix the campaign quantities of item j in period t to those of $t-1$ augmented by the production amount of j at the beginning of t, given that there has been no setup for j in t. Otherwise, these constraints are inactive. The campaign quantities are initialized by the batch size in (2.27).[61] Further bounds on the campaign quantities are provided by (2.28)–(2.30). Constraints (2.28) ensure that the campaign quantity of item j at the end of t must not exceed the quantity of j produced after a setup of j in t. A lower bound for the campaign quantities is set by (2.29). Constraints (2.30) ensure that at least the batch size is produced in each campaign. Moreover, constraints (2.31) and (2.32) restrict the campaign length to an integer number of batches. Constraints (2.31) identify the quantity of item j in period t within an unfinished batch (i.e., the production quantity within an unfinished campaign that exceeds an integer multiple of bs_j) and assign this value to variable S_{jt}. Constraints (2.32), in turn, imply the end of the current campaign (i.e., $S_{jt} = 0$) if there has been a setup on the resource on which j is produced.

The next sets of constraints, (2.33) and (2.34), fix the values for YI_{mt}. Due to (2.33), variable YI_{mt} has to take a value greater than or equal to 1 if resource m has been set up in period t.[62] Furthermore, YI_{mt} is set to zero if no setup occurs on m in t (2.34).

[59] Motivated by the real-world test data of Sect. 6.5, we have formulated this constraint differently to Suerie (2005c, p. 102), where a setup state of 1 is strictly required for all periods $T \setminus \{|T|\}$. A setup state of 0 in periods $T \setminus \{|T|\}$ can be superior to a setup state of 1 if setups in these periods lead to suboptimal (e.g., due to zero demand in early periods) or even infeasible solutions (e.g., if the available capacity in period 1 is smaller than the corresponding setup time, e.g., due to prescheduled maintenance).

[60] Note that variables CAM_{jt} therefore do not necessarily reflect the actual campaign quantity of item j in the current period t; i.e., CAM_{jt} may take positive values although j is not produced in t. This information, however, is sufficient for modeling purposes here.

[61] Again we have chosen a formulation that differs somewhat from that of Suerie (2005c, p. 95). Suerie (2005c) has initialized CAM_{j0} by 0 if $Y_{jt} = 1$, which, however, leads to wrong results if the minimum batch size exceeds one period length. Then, constraints (2.30) would require that the complete batch quantity is produced within a single period if there has not been any setup carry-over into this period [which holds, e.g., in period 1 due to constraints (2.35)]. This may result in infeasible plans or excessive overtime costs.

[62] Note that due to constraints (2.32), variables YI_{mt} cannot exceed 1.

Variables W_{jt} are initialized by (2.35). The remaining constraints (2.36)–(2.40) define decision variables as nonnegative, binary, and integer, respectively.

2.3 Decentralized Planning and Coordination

In this section, we shift our focus from centralized to decentralized supply chain planning. We analyze the inherent lack of coordination in decentralized planning, point out the resulting drawbacks, and motivate the need for coordination, specifically collaborative planning. We start with some basic definitions which are related to coordination and used throughout this work.

2.3.1 Basic Definitions

Supply Chain Coordination

According to Horváth (2001), the term coordination is among the most "dazzling" ones of business economics.[63] First, we consider the meaning of coordination within organizational theory, a classical field of economic research, where coordination is of crucial importance.[64] There, the need for coordination is a direct consequence of the division of labor, which creates single activities with interdependencies among them.[65] Thus, coordination can be regarded as complementary to the division of labor: The re-adjustment of these single activities in order to reach superordinate aims.[66] The essence of this definition is commonly accepted in the literature,[67] although some authors prefer application-oriented definitions, such as: "Coordination is the meshing and balancing of all factors of production or service and of all the departments and business functions so that the company can meet its objectives."[68]

With respect to supply chains, the definitions of coordination in the literature are somewhat more concrete than those mentioned above, but differ substantially from each other. A first stream of literature defines a supply chain as coordinated if and only if actions leading to the supply chain optimum are implemented.[69] A weaker requirement for the actions implemented is an improvement for the whole supply chain compared to the *default solution*, i.e., the solution that would have

63 Horváth (2001, p. 113).

64 See, e.g., Horváth (2001, p. 113).

65 See, e.g., Laux and Liermann (1993, p. 7).

66 See, e.g., Frese (1975, column 2263).

67 See, e.g., Hansmann (2001, p. 255), Horváth (2001, p. 114), and Kieser and Walgenbach (2003, p. 101).

68 Horngren et al. (2006, p. 180) and similar Bhatnagar et al. (1993, p. 142).

69 See, e.g., Cachon (2003, p. 230), who limits the set of contracts that coordinate supply chains to those where "the set of supply chain optimal actions is a Nash equilibrium, i.e., no firm has a profitable unilateral deviation from the set of supply chain optimal actions."

been implemented without coordination. This definition is implicitly supported by Corbett and de Groote (2000), who devise a menu of contracts which results in systemwide costs that are equal to or lower than those of the default solution, but not necessarily equal to those of the systemwide optimum, and call the output "coordinated."[70] Note that the usual default solution in supply chains is characterized by *double marginalization*, where the more powerful parties decide on actions with impact for the whole supply chain and thereby consider their own margins only.[71] A third alternative is to regard any systemwide feasible solution as coordinated, which seems to be favored by Schneeweiß.[72]

We adopt a variant of the alternative secondly mentioned and define that:

> actions coordinate a supply chain if the resulting systemwide profit is greater than that in the default solution.

Our reasoning for this is as follows: The identification of plans which assuredly lead to the exact systemwide optimum is rather an exception in the context of supply chain planning, especially if information asymmetries are present. *Information asymmetry* means that (at least) one party has information that is relevant for decisions concerning all parties but not known by at least one other party.[73] Hence, it would seem misleading to classify the vast majority of approaches which only lead to improvements as non-coordinating. Therefore, we regard the implementation of the optimal actions as a special case of coordination ("optimal coordination"). Note that also in organizational theory,[74] usually no emphasis is placed on the question whether the readjustment of the single actions does lead to the global optimum. The third alternative, i.e., only to require feasibility for coordination, seems least appropriate since it completely ignores aspects of solution quality.

Coordination Scheme, Coordination Mechanism

Next, we introduce two further terms that are closely related to the establishment of coordination and of central importance in this work.[75] We begin with the definition of a coordination scheme:

> A coordination scheme is a set of rules specifying actions whose implementation by decentralized parties potentially coordinates a system.

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[70] See Corbett and de Groote (2000, p. 449); for a detailed description of this approach, see Sect. 3.2.2.

[71] This phenomenon has been recognized first by Spengler (1950, p. 347), much earlier than corresponding advances in the field of supply chain management.

[72] "Worst-case coordination," see Schneeweiss (2003, p. 278).

[73] Explicit definitions of information asymmetry are rare in the literature. See Schneeweiss (2003, p. 219) for a notion of this term similar to ours.

[74] See the literature cited above.

[75] Here, we limit to the definitions of these terms. For examples refer to Chap. 3. Note that in the following, we will abbreviate "coordination mechanism" by "mechanism" and "coordination scheme" by "scheme" if the meaning of these terms is clear from the context.

Note that we do not require here that the application of a coordination scheme always leads to the coordination of a system, which would reduce the scope of this term considerably. Furthermore, a coordination scheme does not necessarily incentives for decentralized parties to follow its rules, i.e., to implement the actions proposed. The definition of a coordination mechanism goes a step further in this respect. It is built on the definition of a mechanism in the field of mechanism design,[76] where a mechanism constitutes a framework that specifies the outcomes (e.g., surplus sharing) of decentralized parties depending on the actions undertaken by them (e.g., their information disclosed):[77]

> A coordination mechanism is a mechanism for which the implementation of the optimal strategies by decentralized, self-interested parties may lead to a coordinated outcome and neither violates the individual rationality of the participating parties nor the budget balance of the system.

Hence, we regard a coordination mechanism as a specific mechanism requiring a potential coordinated outcome and two basic properties in mechanism design, individual rationality and budget balance.[78] *(Ex post) individual rationality* requires that no party is worse off by participating in the mechanism, i.e., that the profits of all participating parties are at least equal to their profits achieved in the default solution. *Budget balance* means that the payments of parties in the mechanism sum up to zero, i.e., that the mechanism does not require an outside subsidy.[79] Moreover, note that a coordination mechanism extends the tasks of a coordination scheme; hence, as in the work, a scheme is often embedded in a mechanism.

Collaborative Supply Chain Planning

The term "collaborative planning" is generally known as a part (and sometimes even regarded as a synonym[80]) of the business practice "Collaborative Planning, Forecasting and Replenishment." As a formalized process, CPFR has been worked out by the standardization committee VICS (Voluntary Interindustry Commerce Standards) and implemented within over 300 companies.[81] The CPFR process model consists of eight planning tasks, which can be subsumed under four main activities: Strategy and planning, demand and supply management, execution, and analysis.[82]

[76] Mechanism design is an area of game theory concerned with the aggregation of unobservable individual preferences into a collective decision, see, e.g., Mas-Colell et al. (1995, p. 857).

[77] Somewhat more technically, in Jackson (2003, p. 2), a mechanism is defined as a "specification of a message space for each individual and an outcome function that maps vectors of messages into social decisions and transfers."

[78] See, e.g., Chu and Shen (2006, p. 1215), who argue that these properties are necessary for mechanisms to be practicable.

[79] See, e.g., Chu and Shen (2006, p. 1215).

[80] See, e.g., Li (2007, p. 159).

[81] See VICS (2008).

[82] See VICS (2008).

"Planning" in this context does not refer to the alignment of operational plans, but to the identification and communication of events which may affect demand, such as promotional activities or product introductions.

Whereas collaboration is restricted to mere information exchange in the original process model, some authors broaden the scope of this term to decision-making. Raghunathan (1999) explicitly includes production scheduling within CPFR.[83] Danese (2005) mentions a concept called "limited CPFR collaboration," where plans are jointly synchronized by the partners (e.g., the replenishment between a central company and a distribution center).[84] Akkermans et al. (2004) describe a business process called "collaborative planning," where companies "jointly take decisions regarding production and shipments for a large part of their collective supply chains."[85]

This notion of collaboration is also included in the definition proposed here:

> Collaborative supply chain planning is a joint decision making process for the alignment of plans of independent, legally separated supply chain parties.

This definition is closely related to that of Stadtler (2009), except for two minor differences. First, we have provided a definition for the term "collaborative supply chain planning" instead of "collaborative planning" in order to avoid potential contradictions to other fields of science dealing with planning for objects different to supply chains. However, since we are only concerned with supply chains in this work, we will use the terms "collaborative supply chain planning" and "collaborative planning" as synonyms in the following. Second, we do not require information asymmetry. In fact, information asymmetry is one of the main reasons for the application of collaborative planning. However, it seems reasonable not to exclude important developments in the field of supply chain coordination that cover uncertain demand or issues of coalition forming, but no asymmetric information.[86]

Finally, it is important to note that a coordination of supply chains made up by legally separated parties cannot be achieved without collaboration. Such supply chains do not comprise a central entity which is entitled to determine the actions of the decentralized parties directly or by means of incentive schemes.[87] As a

[83] See Raghunathan (1999, p. 1054); note that the terminology CFAR instead of CPFR is used there.

[84] See Danese (2005, p. 458).

[85] Akkermans et al. (2004, p. 445).

[86] For a survey of these approaches, see Sect. 3.1.

[87] Mechanisms relying on such entities have been proposed by, e.g., Lee and Whang (1999, p. 633), Pfeiffer (1999, p. 319), Bukchin and Hanany (2007, p. 273), and Kutanoglu and Wu (2006, p. 421). However, these approaches do not ensure the individual rationality of parties. This is feasible if a central entity can entirely determine the costs allocated to the decentralized parties, but seems problematic for general independent parties, who want to improve their gains compared to a default solution. Note in this context that we do not categorically exclude the participation of a central entity in collaborative planning. We only exclude central entities that influence the default solution and thus the individual rationality of parties, but not those that act as mediators and only determine the allocation of the systemwide surplus from coordination (see Sect. 3.3 for examples).

consequence, we will also use the terms "collaborative (supply chain) planning" and "coordination mechanism for supply chain planning" as synonyms in this work.

2.3.2 Decentralized Supply Chain Planning

In this section, we analyze the impact of decentralization on supply chain planning. We argue that decentralized planning may result in suboptimality for a supply chain as a whole and identify the major drivers for that. For ease of exposition, we focus on supply chains consisting of one buyer and one supplier that run the Master Planning models presented in Sect. 2.2. Thereby, we adopt the convention to consider the buyer as female ("she") and the supplier as male ("he").[88] Note that most of our analysis is equally relevant for more general settings, i.e., supply chains with more than two parties and other planning levels.

2.3.2.1 Models for Decentralized Planning

Due to the increasing concentration on core competencies and subsequent outsourcing activities, many supply chains are not run by a single enterprise, but by several, legally separated business units. Under these conditions, an integrated planning for a supply chain as a whole might fail. A major reason for this is information asymmetry: Usually, none of the decentralized parties has the knowledge about all data required for integrated planning. Sharing local production data among decentralized parties, however, is problematic.[89] Private data may be sensitive (especially capacity data[90]) and constitute a strategic advantage for bargaining, which is lost after revelation.

Although this problem is fundamental and matters in most real-world supply chains, current APS do not offer any convincing solution for it. In fact, APS often include tools for collaboration in their planning suites;[91] however, these tools only facilitate the exchange of information, but do not account for the reluctance of decentralized parties to interchange detailed (production) data.

Hence, instead of solving the centralized model, a decentralized party can only determine plans that are valid for its *own planning domain*, i.e., the "part of the supply chain and the related planning processes that is under the control and in the responsibility of one planning organization."[92] For developing mathematical models

[88] This convention is also used within the supply chain contracting literature, e.g., Cachon (2003, p. 230).

[89] This has also been pointed out by , e.g., Arikapuram and Veeramani (2004, p. 111).

[90] As an indicator for the reluctance of practitioners for exchanging production capacities, see the empirical study of Kersten (2003, p. 332).

[91] E.g., SAP (2008) and Oracle (2008).

[92] Kilger et al. (2007, p. 263).

for decentralized planning, consider the interdependencies between the decentralized models that are made up by the inventory balance constraints for the *items supplied*:[93]

$$I_{jt-1} + X_{jt} = \sum_{k \in S_j \cap J^B} r_{jk} X_{kt} + I_{jt} \quad \forall j \in J^D, t \in T. \tag{2.41}$$

Sets

J^B Set of items produced by the buyer
J^D Set of items supplied

These constraints can be reformulated as

$$IB_{jt-1} + XB_{jt} = \sum_{k \in S_j \cap J^B} r_{jk} X_{kt} + IB_{jt} \quad \forall j \in J^D, t \in T, \tag{2.42}$$

$$IS_{jt-1} + X_{jt} = XS_{jt} + IS_{jt} \quad \forall j \in J^D, t \in T, \tag{2.43}$$

$$I_{jt} = IS_{jt} + IB_{jt} \quad \forall j \in J^D, t \in T, \tag{2.44}$$

$$XB_{jt} = XS_{jt} \quad \forall j \in J^D, t \in T, \tag{2.45}$$

$$IB_{jt} \geq 0 \quad \forall j \in J^D, t \in T, \tag{2.46}$$

$$IS_{jt} \geq 0 \quad \forall j \in J^D, t \in T, \tag{2.47}$$

$$XB_{jt} \geq 0 \quad \forall j \in J^D, t \in T, \tag{2.48}$$

$$XS_{jt} \geq 0 \quad \forall j \in J^D, t \in T. \tag{2.49}$$

Variables

IB_{jt} Inventory of the (supplied) item j at the buyer's site in period t; $IB_{j0} = 0$
IS_{jt} Inventory of item j at the supplier's site in period t; $IS_{j0} = 0$
XB_{jt} Amount of item j delivered to the buyer in period t
XS_{jt} Amount of item j delivered by the supplier in period t

(2.42) and (2.43) are inventory balance constraints for the decentralized models. Constraints (2.44) are necessary for the correct computation of the systemwide costs for inventory holding. Constraints (2.45) exclusively comprise the interdependent decisions and link the decentralized models. Constraints (2.46)–(2.49) ensure the nonnegativity of the new variables IB_{jt}, IS_{jt}, XB_{jt}, and XS_{jt}.

The formulations for the decentralized models of buyer and supplier can be derived from a given centralized model by limiting the items and resources modeled to those owned by buyer and supplier and augmenting these models by (2.42) and (2.43), respectively. We denote the decentralized versions of the models of buyer and supplier by adding "S" and "B," respectively, to the model names. Throughout this dissertation, we abbreviate "buyer" by "B" and "supplier" by "S."

93 With "items supplied," we mean the subset of items that may be ordered by the buyer (and subsequently supplied by the supplier)

We take GM as the base model in the following. Since (2.45) comprise decisions of both planning domains, a direct inclusion of these constraints is neither possible in GM-S nor in GM-B. Instead, for modeling decentralized planning, *targets for the supply quantities* have to be incorporated into the decentralized models. I.e., GM-B has to be augmented by

$$xt_{jt} = XB_{jt} \quad \forall j \in J^D, t \in T \tag{2.50}$$

and GM-S by

$$xt_{jt} = XS_{jt} \quad \forall j \in J^D, t \in T. \tag{2.51}$$

Data

xt_{jt} Target for the supply quantity of item j in period t

Without the knowledge of the solution to the centralized model, the target quantities leading to the supply chain optimum can only be determined by chance. In practice, myopic procedures for (unilaterally) determining these targets are employed. Before dealing with these procedures in Sect. 2.3.3, we will point out the major reasons why such myopic procedures often fall short.

2.3.2.2 Drivers for Suboptimality of Decentralized Planning

We have identified a couple of major drivers for systemwide suboptimality due to inappropriate targets for the supply quantities, thereby focusing on the Master Planning models presented in Sect. 2.2. These drivers correspond to the characteristics of these targets that cause elevated costs for one decentralized party and, thus, potentially for the whole supply chain. The knowledge of these drivers is useful for both characterizing settings with a need for coordination and classifying collaborative planning approaches; in fact, all approaches mentioned in the literature review of Chap. 3 can be classified according to the drivers identified here.

In Table 2.3, we provide an overview of the drivers and state their effects on the parties' costs. Three main drivers can be distinguished. The category "time" refers to a temporal over- or undersupply, "lot cycles" to a misalignment of the lot cycles in the supply target, and "quantity" to inappropriate choices of the absolute quantities ordered within the planning interval. In the following, we will explain in more detail how these drivers can lead to increases in the supplier's costs.

Regarding the driver T, two main effects can be distinguished. First, the target supply quantities in early periods of the planning horizon may be too large to be

Table 2.3 Drivers for increases in the supplier's costs

Driver	Impact on parties' costs
Time (T)	Increase of overtime, setup, holding, and backorder costs
Lot cycles (L)	Increase of holding, setup costs
Quantity (Q)	Increase of costs for overtime, lost sales

covered by the supplier's stock and production with normal capacity. In order to fulfill this target, the supplier has to employ costly overtime (see Example 2.1). If the supplier's costs for early supply exceed the costs of the buyer for a potential delay, suboptimality for the whole supply chain results.

Example 2.1 *Consider the supply target for an item in the left of Fig. 2.4. Assume zero initial inventories. Since the possible build-up of stock of this item in period 1 is smaller than the excess supply in period 2, the use of (expensive) overtime is necessary for the supplier.*

Second, the contrary may happen, i.e., the supply may take place too late from the supplier's point of view. Then, elevated holding costs for the supplier may incur if the supplier has to prepone part of his production due to, e.g., restricted production capacity in a later period or scale effects of lot-sizing. The systemwide costs will increase, too, provided that these additional holding costs exceed the cost increase for the buyer due for an earlier order (see Example 2.2).

Example 2.2 *In the right of Fig. 2.4, the supply target for item 3 is depicted. Since the supplier's capacity is partially reserved in period 2, a part of the production of item 3 has to take place in period 1. Let there be end items 1 and 2 with equal holding costs and demand. Let each of these end items require one period length and item 1 one unit (U) of the predecessor item 3 for production. Then the buyer is indifferent which item to produce first, and his choice, i.e., producing item 1 in period 2 (instead of period 1), increases systemwide costs.*

The driver L has two manifestations, too. On the one hand, considering single items, their TBO (= time between orders) may be inappropriate. If an item is ordered too often, the additional costs for supplier's setups or inventory holding may cause systemwide suboptimality (see the following example).

Example 2.3 *Consider a serial supply chain with one end item and one item supplied. For the production of 1[U] of the end item, 1[U] of the item supplied is required. Assume six periods with level end item demand of 1[U] per unit time (UT=1 period), holding costs of 1 monetary unit (MU) per unit and unit time, and setup costs of 2[MU] for both parties. Let the TBO for the supply target be 2[UT] (see Fig. 2.5), as preferred in the local solution of the buyer. This target leads to*

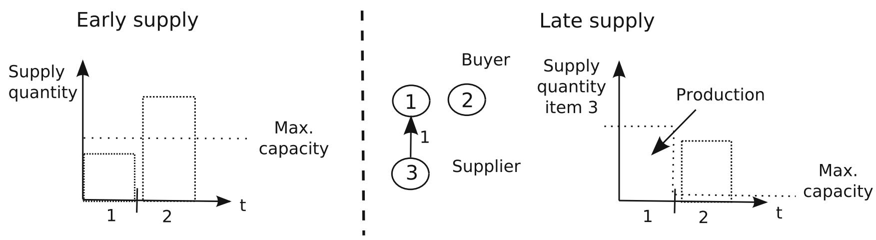

Fig. 2.4 Example for early and late supply

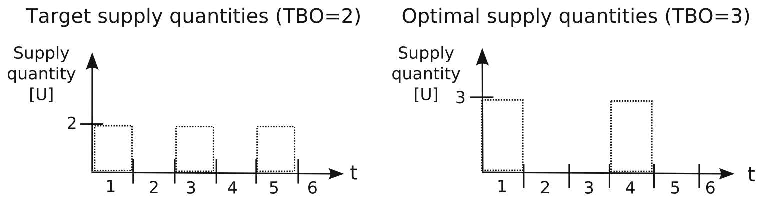

Fig. 2.5 Example for inappropriate TBO

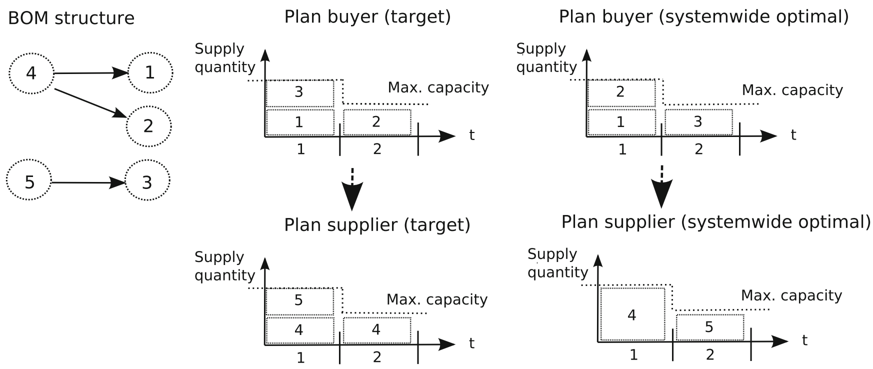

Fig. 2.6 Example for misalignment of lot sizes

systemwide costs of 15[MU] (composed by setup costs of 6[MU] for buyer and supplier as well as holding costs of 3[MU] for the buyer), which exceed 14[MU], the systemwide optimal costs for a TBO of 3[UT].

On the other hand, a misalignment of lot cycles among successor items may further increase the supplier's costs (see Example 2.4).

Example 2.4 *Consider Fig. 2.6. Assume equal demand for all end items (1,2,3) at the end of period 2 and zero initial inventories. Let the production capacity in period 2 be half the capacity in period 1 and setup and inventory holding costs be equal for all end items. Assume that the supply target is one of the buyer's locally optimal plans where items 1 and 3 are produced in period 1 and item 2 in period 2. This plan involves a positive secondary demand for items 4 and 5 in period 1 and for item 4 in period 2. Due to restricted production capacities, the supplier has to set up item 4 twice during the planning horizon to fulfill this demand. The systemwide optimal order, in contrast, goes along with the production of items 1 and 2 in period 1 and the production of item 3 in period 2. This plan involves the same costs for the buyer, but lower costs for the supplier. Since item 4 is exclusively demanded in period 1, the supplier can limit to one setup of item 4 and thus reduce his setup costs.*

The last driver for elevated costs of the supplier is the quantity, i.e., inappropriate relations among the absolute quantities ordered. First, consider one single item supplied. Here, too large target quantities are suboptimal if the resulting overtime of the

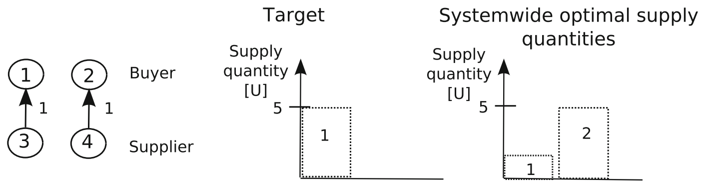

Fig. 2.7 Example for production program as driver

supplier is more expensive than the buyer's lost sales that would occur for smaller supply quantities. Second, for several interdependent items, the relation of their target quantities may be inappropriate as illustrated by the subsequent example.

Example 2.5 *Consider one period and two items supplied. Assume that the buyer produces two items (1,2) with contribution margins of 4[MU] and 3[MU], respectively. Let the maximum demand for these items be 5[U]. The capacity of the buyer's resource is 5 capacity units (CU). Both items 1 and 2 require 1[CU/U] of this resource for their production as well as 1[U] of their predecessor items 3,4 (see Fig. 2.7). Items 3 and 4 are produced on a resource with a capacity of 10[CU]. The production of item 3 requires 4[CU/U] on this resource, and the production of item 4 1[CU/U]. The capacity of this resource can be extended by overtime at costs of 1[MU/U]. Consider a supply target of 5[U] of item 3 and 0[U] of item 4. Although maximizing the buyer's profits, this target is not optimal for the whole supply chain (systemwide profits:* $4 \times 5 - 10 = 10$ *[MU]). Due to the elevated overtime costs for the supplier, the production of 1.25[U] of item 3 and 5[U] of item 4 is more profitable instead (*$4 \times 1.25 + 3 \times 3 = 14$*[MU]).*

For the buyer, analogous drivers can be identified, with the difference that early and late supply have contrary consequences here and that backorders and lost sales may become necessary apart from overtime.

Note that often combinations of these drivers occur, e.g., for the MLCLSP, which comprises capacity restrictions and multi-level lot-sizing. In the presence of specific model characteristics, the impact of the drivers can be considerably aggravated (see Example 2.6).

Example 2.6 *Assume a BOM with two end items which require each 1[U] of an intermediate item for production (see Fig. 2.8a). Let the target supply quantities be equal to the secondary demand for the items supplied (Fig. 2.8b). An implementation of this target avoids overtime at a buyer planning based on the MLCLSP*[94] *(Fig. 2.8c), an insight that proved useful for the design of coordination schemes.*[95] *With the presence of large setup times, however, overtime at the buyer may be required if the capacity consumption of a setup for item 2 is greater than the available*

[94] See Sect. 2.2.2 for this model.

[95] See the scheme of Dudek and Stadtler (2005, p. 673) and that proposed in Chap. 4.

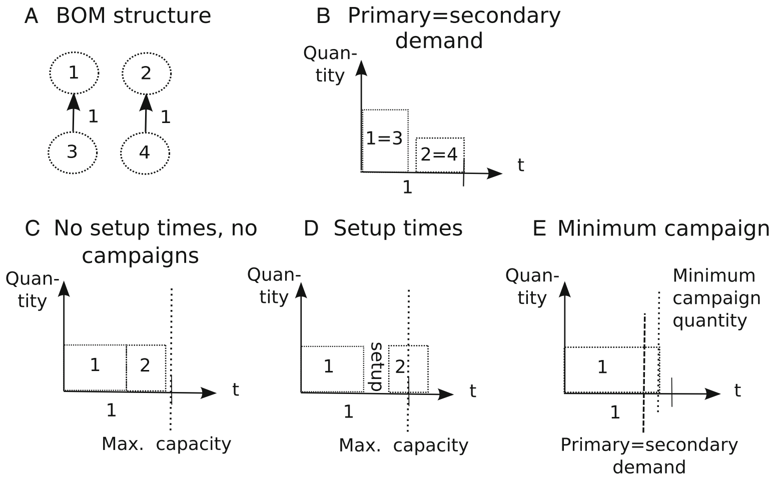

Fig. 2.8 Aggravation of the suboptimality of decentralized planning with setup times and campaign restrictions

slack capacity (Fig. 2.8d). Even worse may be the consequences of minimum campaign quantities (Fig. 2.8e). Here, the campaign for item 1 cannot be started since the supply of item 3 is smaller than the minimum campaign quantity.

2.3.3 Upstream Vs. Collaborative Planning

A common procedure for determining targets for supply quantities is *upstream planning*, i.e., sequential planning starting with the locally optimal plan for the downstream party (here: the buyer). Then this party derives an order for the raw materials required to fulfill her plan and communicates this order to the upstream party (here: the supplier).[96] Depending on the supplier's leeway for order fulfillment, two cases can be distinguished, *full and voluntary compliance* by the supplier.

Forced compliance means that the supplier fulfills the buyer's order without any changes. In the literature, this assumption underlies simulation experiments for evaluating the systemwide suboptimality due to decentralization[97] as well as coordination schemes.[98] As a motivation for the forced compliance case, refer to the use of

[96] In supply chains with more than two tiers, the upstream party would act as an upstream party again and communicate his order to the party at the next tier upstream, and so on.

[97] See Simpson and Erenguc (2001, p. 119) and Simpson (2007, p. 127). Note that in these papers, other terminologies ("pull style planning," "local planning") have been employed instead of "upstream planning."

[98] See, e.g., Dudek and Stadtler (2005, p. 668). There, the term "upstream planning" has been introduced.

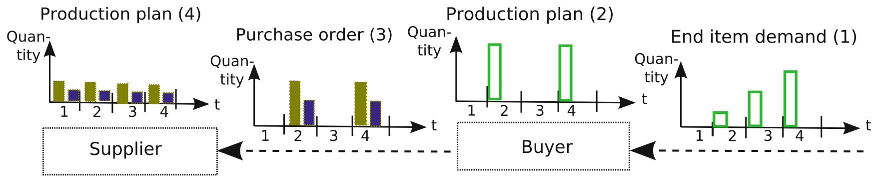

Fig. 2.9 Upstream planning with forced compliance by the supplier

quantity flexibility contracts in practice. There, the supplier has to fulfill the buyer's order completely if the order quantities are kept within a prespecified corridor.[99] We illustrate upstream planning with forced compliance by an example (see also Fig. 2.9).

Example 2.7 *In order to fulfill her end item demand (1), the buyer determines the production plan that is optimal for her planning domain (2). She prefers to produce the demand of period 3 already in period 2 since the associated setup cost reduction exceeds the additional inventory holding costs. Next, the buyer derives via BOM-explosion the amounts of the intermediate items which are necessary to fulfill her production plan and places orders for these intermediate items (3). Finally, the supplier determines a production plan for his planning domain with the restriction of fulfilling the buyer's orders (4). Note that the production of the supplier may differ from the order schedule. Here, the supplier has to prepone a part of production because of tight capacities.*

The mathematical modeling of this planning process is as follows: First, the buyer solves GM-B, thereby assuming an unrestricted delivery of the items supplied. Then she communicates to the supplier the supply quantities xt_{jt}, which are determined by

$$xt_{jt} = \sum_{k \in S_j \cap J^B} r_{jk} X_{kt}.$$

Next, the supplier solves GM-S augmented by (2.51).

An obvious drawback of this procedure is that the supply target is unilaterally determined by the buyer. This renders the resulting solution vulnerable for the drivers for suboptimality affecting the supplier's costs.[100] For uncapacitated lot-sizing problems, the resulting suboptimality has been evaluated by simulation studies. For different parameter settings, average costs increases of 11.5% and 4% compared to upstream planning have been reported.[101] If capacity restrictions come into play, greater suboptimalities can be expected since the overtime costs caused by

[99] See Tsay (1999, p. 1340) for examples for quantity flexibility contracts in industry.
[100] See Table 2.3 on p. 26.
[101] See Simpson and Erenguc (2001, p. 123) and Simpson (2007, p. 133).

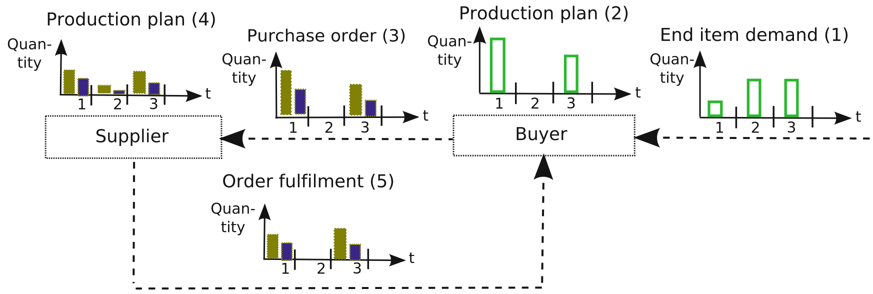

Fig. 2.10 Upstream planning with voluntary compliance by the supplier

inappropriate orders are usually of a higher magnitude than the costs for inventory holding and setups.[102] Usually, this suboptimality increases in case small safety stocks are held by the supplier.

Although forced compliance allows a straightforward determination of the target supply quantities, this assumption cannot always be sustained. Apart from different contractual agreements between buyer and supplier that concede the supplier some (or even infinite) leeway for shortages,[103] the supplier simply might not be able to fulfill the buyer's order – even if he is willing to do so. This occurs, for example, if the supplier has scarce production capacities and is not able to extend them.[104]

Therefore, we further consider voluntary compliance, which means that the supplier is not obliged to exactly fulfill the buyer's order, but can freely choose the extent of his order fulfillment. Below, we provide an example for this (Fig. 2.10).

Example 2.8 *Analogously to Example 2.7, the buyer combines the demands of periods 1 and 2 (1) in her production plan (2) in order to save setup costs and places a corresponding order (3). Here the supplier cannot fulfill this order completely. His optimal production plan (4) results in a reduced supply in period 1 (5). The order fulfillment by the supplier determines the initial, uncoordinated solution. Here, this solution is feasible for the whole supply chain, provided that the resulting lost sales are feasible for the buyer.*

Again, we provide the mathematical modeling for this procedure. First, the buyer solves GM-B and communicates the supply quantities xt_{jt} to the supplier. Next, the supplier determines the extent he is willing to fulfill the buyer's order, thereby taking into account penalties for shortages and lost sales. For this purpose, he solves GM-S with the modified objective function

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[102] Some indications on the resulting suboptimality in capacitated settings provide our computational tests in Chap. 6.

[103] As an example for such agreements, consider the contractual practice in the video rental industry, see, e.g., Cachon and Lariviere (2001b, p. 20).

[104] This may be due, e.g., to technical constraints on the production process such as batch production (see Sect. 2.2.2.2). There, the batch sizes (e.g., volumes of tanks) might not be extendable in medium term.

$$\sum_{j \in J^S} \sum_{t \in T} h_j I_{jt} + \sum_{m \in M^S} \sum_{t \in T} oc_m O_{mt} + \sum_{j \in J^D} \sum_{t \in T} blc_j BL_{jt} + \sum_{j \in J^D} \sum_{t \in T} lsc_j LS_{jt}, \tag{2.52}$$

with M^S as the set of resources of the supplier and modified inventory balances for the items supplied:

$$I_{jt-1} + X_{jt} + BL_{jt} + LS_{jt} = BL_{jt-1} + I_{jt} + xt_{jt} \quad \forall j \in J^D, t \in T. \tag{2.53}$$

Finally, the buyer solves GM-B augmented by

$$xt'_{jt} = \sum_{k \in S_j \cap J^B} r_{jk} X_{kt} \quad \forall j \in J^D, t \in T,$$

with modified supply quantities xt'_{jt} derived from the outcome of the supplier's model:

$$xt'_{jt} = xt_{jt} - BL_{jt} - LS_{jt} + BL_{jt-1}.$$

Like in the forced compliance case, systemwide suboptimality may result from inappropriate orders of the buyer. Moreover, inappropriate shortages by the supplier may trigger elevated costs for the buyer. A further potential drawback of this procedure is the missing guarantee for feasibility in the presence of particular restrictions such as shelf-life or storage capacity restrictions (see Example 2.9).

Example 2.9 *Assume that the supplier delivers two intermediate items that are assembled by the buyer to an end item. Given zero initial inventories, the buyer will order these items in an equal relation, of course. Assume that the supplier can only fulfill the order of one of these items due to restrictions on his production capacities. Since the buyer cannot perform the assembly then, she would have to keep the supplier's delivery in stock. If her storage capacities are too scarce, then the supplier's delivery might be infeasible for her. Simply choosing a lower supply than offered by the supplier, however, does not necessarily establish systemwide feasibility if the supplier's storage capacity is restricted, too.*

Summarizing, upstream planning may lead to suboptimal plans and even bears the risk of generating infeasible solutions. In this work, we present a remedy for this: Collaborative planning. We propose that decentralized parties do not settle for the solution from upstream planning, but collaborate in order to identify a feasible supply target with costs coming near to the systemwide optimum.

While upstream planning is based on unilateral targets, collaborative planning takes the preferences of all decentralized parties into account. It aims to combine the advantages of centralized and decentralized planning, i.e., to reach an appropriate solution quality without exchanging detailed information about the decentralized parties' production processes. The collaborative planning mechanisms proposed in this work operate as add-ons to improve a default solution, which, e.g., may result from upstream planning. They try to identify an improvement by an iterative

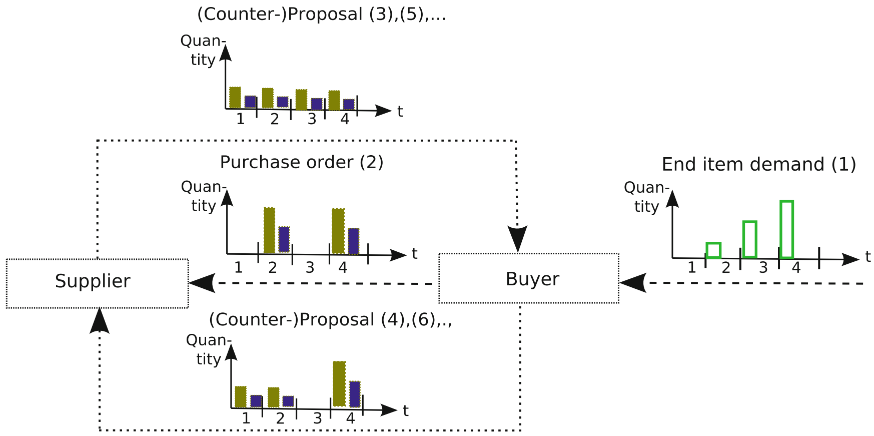

Fig. 2.11 Collaborative planning

exchange of several supply proposals, with the chance that one of these proposals is superior to the target determined by upstream planning. We illustrate this process by an example (see also Fig. 2.11).

Example 2.10 *Consider upstream planning with forced compliance. The buyer's demand (1) and purchase order (2) are taken from Example 2.7. Now, apart from upstream planning (2), parties iteratively interchange supply proposals in order to identify an improved solution for the whole supply chain. Here the supplier proposes a more equal temporal distribution of the supply quantities to increase his capacity utilization (3), and the buyer adapts this proposal by aggregating the supply of periods 3 and 4 (4). Steps (5),(6), . . . stand for further proposals generated, which are not depicted in Fig. 2.11 for ease of exposition.*

The main challenges for carrying out such a collaborative planning process are the identification of potentially coordinating proposals and the assurance that the coordination process is supported by the incentives of self-interested decentralized parties. Both issues are tackled by the new mechanisms proposed in Chaps. 4 and 5.

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