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ORIGINAL PAPER



Decentralized modular production to increase supply chain efficiency in chemical markets

An example of polymer production

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Abstract

In the chemical industry, shortened product life cycles and greater differentiation of customer demand increase challenges to efficiently meet specific customer requirements. Thus, production systems with high flexibility are required. One innovative production concept that meets this requirement is decentralized, small-scale modular production which offers significantly more flexibility in the tactical configuration of the production network. Corresponding production plants are assembled from standardized apparatus modules in transportation containers, hereby enabling a fast relocation of modular plants and adjustments of the production process. Therefore, modular plants can be operated close to customers or suppliers, which supports local sourcing strategies and a reduction in delivery costs. In this paper, we analyze the advantages of these modular production systems for a case from the specialty chemicals industry. Respective advantages arise especially from a technically flexible design of parallel process lines, autonomous production and local sourcing. In order to evaluate economic efficiency and network configuration of modular production networks, an efficient mathematical formulation for the optimization is proposed. This formulation includes a new way to model relocations of modules. We apply this model to a case based on real data from the chemical industry. As a result of this application we come to three technical and managerial conclusions. Firstly, technical designs with parallel process lines improve flexibility and efficiency compared to mono processes. Secondly, autonomous production increases economic efficiency in contrast to staffed production and finally, local sourcing offers significant cost reduction potential compared to central sourcing.

Keywords Small-scale modular production \cdot Chemical industry \cdot Network optimization \cdot Decentralized production network \cdot Supply chain

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JEL Classification $C02 \cdot C61 \cdot L23 \cdot L65 \cdot O14$

1 Introduction

In the chemical industry, shorter product life cycles and greater differentiation leads to increasing difficulties in predicting and meeting customer demand. One innovative production concept that fulfills these requirements is small-scale modular production, for which the first prototypical chemical plants have already been deployed. These modular plants can be swiftly assembled from standardized apparatuses and can be installed in transportation containers. It is possible to quickly relocate modular plants or to change the production process. Additionally, production capacities can be scaled by adding or removing modular plants. Therefore, it is possible to operate modular plants near to suppliers or customers and to react dynamically to changes in demand (Buchholz 2010). Prototypical modular production concepts have been developed by major players in the chemical industry, including BASF, Bayer, Evonik, Procter & Gamble and AstraZeneca. Some examples for modular production processes comprise pharmaceutical intermediates, biomass-based chemicals and specialty chemicals (European Commission 2014).

In comparison to conventional manufacturing methods, modular production concepts offer significantly more flexibility in the tactical configuration of the production network. Due to the flexibility in capacity, process and location, various decisions shift from the strategic to the tactical level of production network planning. This implies an increased complexity of the tactical planning (Becker et al. 2019). To take full advantage of the benefits of modular systems, all flexibility options must be taken into account. For this reason, we have developed a mathematical formulation for the tactical production network planning with modular production concepts.

For an economic evaluation of the modular concept proposed in this paper, it is essential to specify the application area: individually tailored specialized polymers form a fast growing segment of the chemical industry. These polymers are usually produced in small quantities and it may not be profitable to produce an entire batch with a conventional batch system. Therefore, a large-scale case study for this segment was conducted to discuss the effects of modularization in more detail, which includes real-world data from a chemical company. As in this case study, the costs of raw materials often represent an important fraction of the overall cost in the chemical industry, especially when downstream production steps are examined (Ekici 2013). In this regard, decentralized production opens up new degrees of freedom in terms of distributed facilities and site selection and thereby a further advantage in the case of specialty polymer production: since the final products often consist to a large extent of commonly available raw materials, local sourcing options can be exploited to broaden the selection of suppliers and further reduce logistics costs.

On the contrary, one disadvantage of modular production is the reduction of economies of scale. This applies not only to the production equipment but also to the staff: many decentral sites are more staff intensive compared to one central site. In order to cope with this challenge, innovative digital ways of remote control and remote maintenance open up opportunities for autonomous production, going along with the current fourth industrial revolution. In this paper, the following research questions will be answered:

- What is the impact of small-scale modular production concepts on specialty chemical supply chains?
- What is an appropriate mathematical optimization model for the planning of specialty chemicals production networks with modular production concepts?
- Which benefits do modular production concepts and their configuration offer for specialty chemicals supply chains, especially with respect to process flexibility (leading to product flexibility), autonomous production and local sourcing?

The paper is structured as follows: in Sect. 2, the opportunities of small-scale modular production concepts for the chemical industries are characterized. Section 3 discusses the impact of modular production concepts on the specialty polymers supply chain and production process. Section 4 presents a new mathematical formulation for the tactical planning of modular production networks for the introduced case from the specialty chemicals industry. In Sect. 5, the benefits of modular production concepts are discussed on the basis of a case with real-world data. Section 6 provides a brief conclusion and indications for future research.

2 Small-scale modular production systems in the chemical industry

This section gives an introduction to the key ideas of small-scale modular production and discusses the potentials for chemical production.

2.1 Implementation of modular plants

In the chemical industry, the concept of small-scale modular production plants combines the ideas of standardization and modularization. A modular production plant consists of multiple independently functioning autonomous units, each of which serves a certain purpose within the production process (Wörsdörfer et al. 2016). All necessary mass and information flows are provided by the connected periphery (Bieringer et al. 2013). Within the production plant, the modularization is implemented with standardized, exchangeable apparatuses. New production processes can be deployed quickly as they do not undergo the very time consuming scaling process from laboratory scale over technical scale up to production scale. This enables a shorter time to market in comparison to an individually designed process that is optimized for a single use case.

The production process of a modular production plant can be adapted to changing customer demand by a reconfiguration. A reconfiguration changes the number and type of apparatuses used by a modular plant. This can be compared to the LEGO[©] principle (Kaczmarek et al. 2015). Hence, a high compatibility of apparatuses is a key requirement for the proposed production setting.

In contrast to large-scale production systems, modular plants can be easily relocated. Thus, it is viable to operate modular plants in proximity to suppliers or customers. Additionally, process control systems enable an autonomous operation of modular plants so that personnel costs can be reduced. Decentralized production facilities can then be remotely operated, maintained and monitored. This enables new business models for automation technology and apparatus suppliers. Companies gather information on production processes in a central module database. For each available process configuration, the required apparatus as well as the operational parameters are recorded (Hady and Wozny 2012). Further, the production of multiple product families at each location can be realized by simultaneously operating multiple modular plants. Each plant can implement different processes and thus a large product diversity can be reached. The use of decentralized modular plants facilitates major changes in conventional process industry business models (Lier et al. 2013).

Overall, modular production concepts increase the tactical and operational flexibility of the production network. There are three levels of modularity in the modular production network. We refer to individual apparatuses (first level), which jointly define a modular production plant (second level). Production facilities represent the highest level of modularity: their capacity is defined by selecting the number and type of modular production plants.

2.2 Opportunities for the chemical industry

In the chemical industry today, large-scale production systems are the predominant mode of production. These can be subdivided into continuously operated single product plants and multi-product plants, which are typically operated in a batch mode. A continuous mode of operation is most suitable for large-scale commodity production when it is possible to exploit economies of scale. Single product plants are very efficient but typically lack the flexibility to react to changes in demand. Multi-product plants on the other hand are very quick in adapting to uncertain market situations and changing demand structures. They are used for high-valued products which are typically produced in small quantities (Rauch 2006). Between product batches of different types, the process has to be changed. This results into long downtime. Furthermore, in comparison to single-product plants, multi-product plants are often inefficient with respect to energy and material consumption (Seifert et al. 2012).

Small-scale modular production plants can combine some of the benefits associated with large-scale continuous plants and batch plants. Modular plants are ideally operated in a continuous production mode. Thus, each modular plant is equipped with an optimized production process for a limited set of products. At the same time, a high product flexibility is maintained as the process can be changed quickly by reconfiguring modular plants. In the literature, there are different definitions for flexibility in chemical production systems. Three different types of flexibility are evident in a modular production network: product flexibility, capacity flexibility and location flexibility (Becker et al. 2019). Figure 1 gives



Fig. 1 Schematic visualization of the different options of flexibility for modular production plants

a schematic visualization of the mentioned types of flexibility. The proposed modular production plant consists of a combination of different chemical process equipment. In this visualization, the different graphical forms represent the apparatuses, which are installed in a modular production plant.

Product flexibility of modular production systems is achieved by either changing the equipment installed in a modular production system or by using multiple production lines in a single modular plant. The operating range of a large-scale plant is typically determined at the time of construction. Subsequently, capacity adjustments are limited to this range. In contrast, the capacity of modular production systems can be easily adjusted by adding more modular plants to a facility. Therefore, modular production systems are associated with a high *volume flexibility*, i.e. the ability of a production system to change its production volume while the overall structure of the production system is not impaired. In a volatile market situation, volume flexibility offers the opportunity to react quickly to increasing or decreasing customer demand.

A further advantage of modular production plants in comparison to large-scale plants is the ability to relocate modular plants at short notice. Large-scale production plants are built and operated over a long period of time. In contrast to large-scale plants, modular plants can be installed in standard transport containers and relocated with minimum effort by truck (Bieringer et al. 2013; Lang et al. 2011), thus *location flexibility* is obtained. As modular production facilities can be established at short notice, new opportunities arise with regard to the supply chain and production network structure. If demand shifts regionally, modular production plants can be quickly relocated in response. Thus, decentralized production can potentially reduce the required transportation distance associated with sourcing and distribution activities, resulting in reduced logistics costs and CO_2 emissions.

Small-scale modular production systems are especially well suited for highly customized products, as economies-of-scale are less important in this market segment. In the following section, we discuss the impact of modular production concepts on the supply chain for the specialty chemicals industry.

3 Modular production of specialty chemicals

In this section, we describe the structure of the supply chain for specialty chemicals and the effects of modular production concepts thereon. Furthermore, we provide an overview of the production process that we consider for our further investigations.

3.1 Structure of the specialty chemicals supply chain

Chemical industry supply chains cover a wide variety of logistics and manufacturing activities (Kadipasaoglu et al. 2008), from the large-scale production of base chemicals to the individual customization. A comprehensive review of the work on process industry supply chains can be found in Shah (2005). In comparison to the overall set of products offered at later stages of the supply chain, there are typically few base polymers which rarely change.

Usually, base polymers are produced in an optimized production process on large-scale plants. In contrast, small-scale modular production concepts offer great potentials for use in the later stages of the chemical industry supply chain, in which the product portfolio is highly diversified and changes occur frequently. Our further discussion focuses on the use of modular production concepts for the production of specialty chemicals in the later stages of the supply chain. Currently, batch plants are used in case of high variability in the product portfolio or demand volume, but there are limits with respect to the responsiveness of a supply chain if batch plants are used. The new flexibility options of modular production concepts has a strong impact on the supply chain structure.

3.2 Impact of modular production concepts

From the perspective of a company involved in specialty chemicals, production comprises a typical conventional supply chain structure with three or four nodes with a clear hierarchy. Suppliers deliver raw materials to production facilities. These are processed at those facilities, and processed goods are either delivered to warehouses or directly to the customer. Warehouses are an optional node that can reduce logistics costs by pooling deliveries. In that case, deliveries are relayed via the warehouse on their route from the production facility to the customer.

This structure of supply chain nodes and flows is changed by the introduction of modular production concepts, for which we have identified four types of nodes. These are suppliers, modular production facilities, customers and modular hubs. Modular hubs are required as workshops for the storage, assembly, deployment, dismantling and maintenance of modular plants. Since modular plants can be operated at decentral facilities, they can be placed in proximity to customers and/or raw materials. In the customization of specialty chemicals, modular plants are typically located near customers. This is due to the expensive distribution logistics for a high number of low to medium amounts of specialties in comparison to sourcing costs. Raw materials can be pooled more efficiently when delivered to production facilities. By locating production facilities near customers, the cost and complexity of distribution logistics can be reduced. As a result, modular production facilities are connected to customers for distribution and on the previous level to suppliers and modular hubs. Modular production facilities have to be equipped with the required modular plants.

Owing to the new flexibility options, the production capacity can be adjusted on an operational to tactical level. Modular hubs assemble and deliver the required modular plants to modular production facilities. In addition, there are reverse flows from modular production facilities to modular hubs when a modular plant is not required anymore. Flows of modular plants between modular production facilities occur if there is a locational shift of demand. Figure 2 gives an exemplary visualization of the changed structure of the specialty chemicals supply chain. To realize small-scale modular production in proximity to the customer, a suitable implementation of the production process is necessary. Therefore, the technical implementation of the production process is described in the following section for an exemplary process which is typical for the production of specialty polymers. The process is also used in conjunction with the previously discussed supply chain as basis for the model and scenarios in our case study (Sects. 4 and 5).

3.3 Production process

The process under consideration is the final step in the production of special polymers. These specialized polymers are produced by mixing a base polymer with selected additives. Two different approaches are considered here: Firstly, the production of specialized polymers in the current industrial state through a discontinuous production plant; secondly, the production of specialized polymers in multiple modular continuously operated production plants.

In the current state, the base polymers are processed in discontinuously operated standard multi-product plants. Here, the base polymers are heated in agitated vessels



Fig. 2 Excerpt of the supply chain changed by modular production concepts

to a certain temperature. Shortly after the additives are added, the mixture is stirred until a homogeneous state is reached. By using additives, the characteristics of the base polymers can be adjusted, e.g. with regard to their color, their ability of resisting ultraviolet light (UV-protection) and their softening (plasticizer). After a homogeneous state is reached, the agitated vessels are emptied and cleaned for the next batch. This cycle of filling, mixing, emptying and cleaning is known as batch or discontinuous production. A significant disadvantage of discontinuous production is the idle time caused by emptying and cleaning the agitated vessels. In addition, there are constraints with regard to the minimum production quantity for batch production. For very small quantities, it might not be economically or technically feasible to produce a whole batch.

In order to implement the described special polymer process in a continuous way for modular production plants, a different mixing approach is required, taking into account the limited space of a modular plant. Therefore, instead of an agitated vessel, a static mixer is used as the mixing apparatus. A static mixer consists of a tubular housing with static mixing structures, so no moving parts are needed. The static mixer enables the change from batch to continuous production. Figure 3 shows the process flow chart of the proposed production process of specialized polymers in a modular production plant.

The process consists of separate containers (production, cleaning, and additive container), each of which serves a particular task. In this example, three different base polymers with different viscosities are used as production inputs. It is assumed that the used additives are inert, miscible and no hazardous contaminants. The base polymer is pumped with an eccentric screw pump from tanks to the production container. In the production container, the base polymer is heated up to a specific temperature using process steam in a heat exchanger. Once the required temperature is



Fig. 3 Process flow chart for the described implementation of a modular production system

reached, the base polymer is mixed in the continuous static mixer with the selected additives that are pumped from barrels out of the additives container. Pipes and mixers can be cleaned with a solvent, which is then regenerated in the cleaning container. The regeneration takes place in a membrane-module within the cleaning container. This leads to a minimal solvent loss. In the following, we distinguish products only by the base polymer used. Different products result from a single base polymer by adding various additives. All products of such a product family can be produced on the same production unit and will be aggregated and referred to as one product type.

The described plant layout is well suited for decentralized production as it can easily be assembled and deployed because it depends only on standard utilities. The next section describes the tactical production network planning associated with the discussed implementation.

4 Methodology

The concept of small-scale modular production opens up the possibility of production close to customers or suppliers. To evaluate the benefits of decentral modular production, we conduct a case study based on real customer data from the chemical industry. The production process for the case of specialty polymers production was described in the previous section. In this section, we first provide a literature review on mathematical models for related planning problems. Then, we propose a new mathematical model for the tactical planning of modular production networks that captures all features required for our case. On the basis of our mathematical model, we describe the experimental setting and different scenarios that we created to evaluate the economic impact of decentral, modular production on the production network, including some additional opportunities offered thereby.

4.1 Literature review

The tactical planning of a modular production network with relocatable plants can be seen as a special type of a facility location problem. There is a vast literature on facility location and supply chain network design. Many papers deal with applications and propose problem specific models, whereas some investigate general models with a varying range of features. A general survey is given by Melo et al. (2009). Martínez-Costa et al. (2014) review mathematical models for strategic capacity planning. A review of flexibility options available in tactical supply chain planning models is given by Esmaeilikia et al. (2016). A large number of studies investigate dynamic location and capacity planning problems with the possibility to modify the set of active facilities and the capacity level of each. The planning of a specialty chemicals modular production network can be characterized as a dynamic multiproduct facility location problem with multiple modular capacity levels at each facility. The two tier structure of capacities represents a special feature, since capacities are delivered to production facilities from a special type of upstream facility. Furthermore, discrete capacity modules can be relocated between facilities to adjust the capacity level. In the scope of facility location, relocations are typically modeled by closing a site at one location and reopening it at another one. This does not adequately represent the situation in a modular production network. Modular production plants can be physically relocated from one site to another, i.e. the equipment is transferred between the two sites. Thus, it is important to explicitly model the relocation of discrete capacity modules.

Melo et al. (2006) propose a general mathematical formulation for supply chain planning. They consider opening and closing of facilities over the planning horizon, as well as capacity expansions and reductions. Furthermore, they describe an extension to their modeling framework to consider modular capacity shifts between locations. Tsiakis and Papageorgiou (2008) propose a mathematical formulation for the configuration of a production and distribution network that is applied to a case from the specialty chemicals industry, but they do not consider modular production. Ferrio and Wassick (2008) model a chemical supply chain network to optimize the flow of multiple products to customers. Their model considers customers individually, instead of an aggregation. In this way, a detailed cost accounting for the costs of the supply chain with respect to each customer is possible. However, they focus on material flows and do not consider a detailed account of the fixed cost of facilities and the capacity level. Hein and Almeder (2016) consider a problem where vehicles have to be routed for raw material collection from multiple suppliers prior to production of the final product. They note that cost savings are obtained by solving an integrated problem. Hsu and Li (2009) investigate a model for integrated capacity and production planning. They compare the use of many small-scale plants with the operation of few large-sized capacity plants within the scope of economies of scale. Their case study shows that the cost savings of centralized production outweighs the reduced transportation cost. Jena et al. (2015) discuss a new general formulation for facility location and capacity planning that allows facility closing and reopening and capacity expansions and reductions. They prove dominance relationships between their formulation and existing formulations for special cases. While they include facility relocations, no formulation is provided for the relocation of capacity modules of discrete size.

The influence of demand uncertainty and the option of plant reconfigurations on the planning of a modular plant production network has already been discussed (Becker et al. 2018a, b). Becker et al. (2019) present several mathematical formulations that incorporate different types of flexibility provided by modular production concepts. They propose a variant of their *Dynamic Network Configuration* model that considers the additional flexibility of modular plants. Their mathematical formulation can be solved in a reasonable amount of time for a number of ten production facilities.

Many of the important aspects associated with modular production network design are captured by existing mathematical models (Becker et al. 2019; Jena et al. 2015; Melo et al. 2006). However, there is no single model that meets all requirements of the situation in this paper. Specifically, we are not aware of a model that

considers discrete capacity modules of different types in a multi-commodity setting in combination with explicit supplier selection which can be solved for larger instances. Thus, in the following a mathematical formulation is proposed for the tactical planning of modular production networks with supplier selection for the case of specialty polymer production. Furthermore, the model uses a new way to model the relocation of discrete capacity modules. Utilizing the new mathematical formulation, problem instances with 100 production facilities were optimally solved.

4.2 Mathematical model

In the following, we provide a model formulation for the planning tasks related to the case presented throughout this paper. We use the mathematical formulation to obtain optimal solutions for all different scenarios in our case study.

An overview of the symbols and notation used by our mathematical formulation is given in Table 1.

We develop a mathematical model for a company in the specialty polymers industry. This market is characterized by a make-to-order setting. The aim is to establish a minimum cost production network to fulfill all customer orders over all periods of the planning horizon. For each period, it has to be decided which facilities to operate and how many modular plants of each type to install. Furthermore, it must be decided which production site executes each customer order. Additionally, a sufficient quantity of base polymers and additives has to be transported to the production facilities.

To account for the flexibility of modular production concepts, we select a time horizon of one year, since a modular production network can be configured on the tactical level (Becker et al. 2019). We consider 12 months as time periods $t \in T$ across the planning horizon. Time period t = 0 is not contained in T, as it serves as an auxiliary period for the setup of the production network. The set of production facilities is denoted by *I*. These are industrial and chemical parks where plots suitable for the operation of modular plants can be rented. In addition to the legal requirements for chemical production sites, sufficient space and the necessary utilities must be available. We separately denote the modular hub by $i = 0 \notin I$. We assume that all modular plants are assembled at the modular hub, before they are deployed to production facilities. The modular hub represents a central large-scale facility of the company operating the modular production network. No modular plants are operated at the modular hub. The modular production network can be initially setup in time period t = 0, since no demand occurs. The number of modular plants at a facility is specified by the capacity level $m \in M$. The set of capacity levels M contains a high number of capacity levels that will not be exhausted. In this way, the model can select the optimal capacity level of each facility without restraint. Furthermore, we consider three different product families $p \in P$ which differ in terms of the required base polymer. Each product family may contain several hundred individual products which are obtained by combining the base polymers with a low amount of additives.

Index sets	
Ι	Set of facilities suitable for modular production
S	Set of base polymer suppliers
G	Set of modular plant configurations
Μ	Set of possible modular capacity levels
J	Set of customers
Р	Set of products
Т	Set of time periods
Cost and production	on parameters
c_{ip}^{var}	Unit production costs of product p at facility i
c_{iin}^{tp}	Unit transportation costs of product p from facility i to customer j
c_i^{add}	Unit transportation costs for additives to facility <i>i</i>
c_{si}^{bp}	Unit transportation costs of base polymers from supplier s to facility i
c_i^{loc}	Operational costs of facility i per period
c ^{mod}	Depreciation per modular plant over the planning horizon
c_i^{op}	Operational costs per modular plant and period at facility i
$C_{ii'}^{reloc}$	Relocation cost for a modular plant from facility i to i' (including relocation costs from and to the hub)
f^{bp}	Proportion of base polymers required per unit of production
f^{add}	Proportion of additives required per unit of production
D_{ipt}	Demand of customer <i>j</i> for product <i>p</i> in period <i>t</i>
Cap _s ^{raw}	Maximum capacity of supplier s per time period
Cap_{gp}^{prod}	Capacity per modular plant of configuration g for product p
Decision variables	
$x_{ipt} \ge 0$	Amount of product p produced at facility i in period t
$z_{ijpt} \ge 0$	Amount of product p delivered from facility i to customer j in period t
$v_{it} \ge 0$	Amount of additives transported to facility i in period t
$u_{sit} \ge 0$	Amount of base polymers transported from supplier s to facility i in period t
$y_{igmt} \in \{0,1\}$	The binary variable indicates whether a number of m modular plants of configura- tion g are operated at facility i in period t or not
$y_{0gm0} \in \{0,1\}$	The binary variable indicates whether a number of m modular plants of configura- tion g are acquired at the modular hub at the beginning of the planning horizon
$\delta_{it} \in \{0,1\}$	The binary variable indicates whether facility <i>i</i> operates in period <i>t</i> or not
$r_{ii'gt} \in \mathbb{N}_0$	Integer variable that denotes the number of modular plants transported from facility i to i' in period t

Table 1	Overview of symbols used by our mathematical formulation	on

On a tactical planning level, an aggregation to product families is adequate because changeover times are negligible.

In the following, we state the mathematical model for our case.

$$\min \sum_{i \in I} \sum_{p \in P} \sum_{t \in T} c_{ip}^{var} x_{ipt} + \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} c_{ijp}^{tp} z_{ijpt} + \sum_{i \in I} \sum_{t \in T} c_i^{add} v_{it} + \sum_{s \in S} \sum_{i \in I} \sum_{t \in T} c_{si}^{bp} u_{sit} + \sum_{i \in I} \sum_{t \in T} c_i^{loc} \delta_{it} + \sum_{g \in G} \sum_{m \in M} m \cdot c^{mod} y_{0gm0} + \sum_{i \in I} \sum_{m \in M} \sum_{g \in G} \sum_{t \in T} m \cdot c_i^{op} y_{igmt} + \sum_{i \in I \cup \{0\}} \sum_{i' \in I \cup \{0\}} \sum_{g \in G} \sum_{t \in T \cup \{0\}} c_{ii'}^{reloc} r_{ii'gt}$$

$$(1)$$

s.t.
$$\sum_{i \in I} z_{ijpt} = D_{jpt} \quad \forall j \in J, \ p \in P, t \in T$$
(2)

$$\sum_{j \in J} z_{ijpt} \le x_{ipt} \quad \forall i \in I, \ p \in P, \ t \in T$$
(3)

$$x_{ipt} \le \sum_{m \in M} \sum_{g \in G} m \cdot Cap_{gp}^{prod} y_{igmt} \quad \forall i \in I, \ p \in P, \ t \in T$$
(4)

$$\sum_{i \in I} u_{sit} \le Cap_s^{raw} \quad \forall s \in S, \ t \in T$$
(5)

$$\sum_{p \in P} x_{ipt} \le \sum_{s \in S} \frac{1}{f^{bp}} u_{sit} \quad \forall i \in I, \ t \in T$$
(6)

$$\sum_{p \in P} x_{ipt} \le \frac{1}{f^{add}} v_{it} \quad \forall i \in I, \ t \in T$$
(7)

$$\sum_{m_1 \in M} m_1 y_{igm_1 t} - \sum_{m_2 \in M} m_2 y_{igm_2(t-1)}$$

=
$$\sum_{i' \in I \cup \{0\}} (r_{i'ig(t-1)} - r_{ii'g(t-1)}) \quad \forall i \in I \cup \{0\}, \ g \in G, \ t \in T$$
(8)

$$\sum_{m \in M} y_{igmt} \le 1 \quad \forall i \in I \cup \{0\}, \ g \in G, \ t \in T \cup \{0\}$$
(9)

$$y_{igm0} = 0 \quad \forall i \in I, \ g \in G, \ m \in M$$
(10)

$$y_{igmt} \le \delta_{it} \quad \forall i \in I, \ g \in G, \ m \in M, \ t \in T$$
(11)

$$\delta_{it} \ge \delta_{i(t-1)} \quad \forall i \in I, \ t \in T, \ t > 1$$
(12)

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$$\sum_{i' \in I} r_{ii'g0} = 0 \quad \forall i \in I, \ g \in G$$
(13)

 $x_{ipt}, z_{ijpt}, v_{it}, u_{sit} \ge 0 \quad \forall s \in S, \ i \in I, \ j \in J, \ p \in P, \ t \in T$ (14)

i

$$\delta_{it} \in \{0, 1\} \quad \forall i \in I, \ t \in T \tag{15}$$

$$y_{igmt} \in \{0,1\} \quad \forall i \in I \cup \{0\}, \ g \in G, \ m \in M, \ t \in T \cup \{0\}$$
(16)

$$r_{ii'gt} \in \mathbb{N}_0 \quad i \in I \cup \{0\}, \ i' \in I \cup \{0\}, \ g \in G, \ t \in T \cup \{0\}.$$
(17)

Variable $x_{ipt} \ge 0$ specifies the production quantity of product *p* at facility *i* in period *t*. The quantity of product *p* shipped from facility *i* to customer *j* in period *t* is determined by variable $z_{ijpt} \ge 0$. The amount of base polymers shipped from supplier *s* to facility *i* in period *t* is denoted by variable $u_{sit} \ge 0$. Variable v_{it} specifies the quantity of additives shipped to facility *i* in period *t*. The binary variable $y_{igmt} \in \{0, 1\}$ indicates whether a number of *m* modular plants of configuration *g* are operated at facility *i* in period *t*. Whether facility *i* is operated in period *t* is defined by the binary variable $\delta_{it} \in \{0, 1\}$. The number of plant relocations of configuration *g* from facility *i* to *i'* in period *t* is denoted by variable $r_{ii'gt} \in \mathbb{N}_0$.

The objective function minimizes the total costs of establishing and operating the production network (Eq. 1). The first term of the objective determines the variable production costs. The variable production costs are tied directly to the production of an additional unit of product p at facility i. As the local prices for e.g. utilities vary, these costs may differ between facilities.

The second to fourth term denote the material logistics costs in the production network. This comprises deliveries of finished products from production facilities to customers and transportation of additives and base polymers to production facilities. We assume road transportation by truck for all logistics activities. Transportation costs are differentiated by less than full truck load (LTL) and full truck load (FTL) transportation. We assume that base polymers are shipped in FTL mode, because of the high quantities required for production. Since both additives and the final product are highly specialized, shipments typically involve smaller quantities, such as a few barrels. Thus, we assume that these are transported in LTL mode. We combine the shipping cost per t/km, differentiated by mode, with the road distance between origin and destination to obtain the transportation costs c_{ip}^{tp} , c_i^{add} and c_{si}^{bp} . For base polymer deliveries, there is a set of suppliers $s \in S$ that may supply production facilities. The specialized additives, however, have to be delivered from the modular hub. Therefore, the additive shipping costs only have a destination index, since the origin is always the modular hub.

In each period a facility is active, operational costs for the facility c_i^{loc} (fifth term) are incurred. It includes the costs of human resources needed for supervision of operations at each active production facility. The sixth term of the objective denotes the depreciation per modular plant c^{mod} over the planning horizon.

In addition, we consider operations and maintenance charge per active modular plant and time period at a facility c_i^{op} (seventh term). The operational costs of facilities and modules may also differ between facilities, since local prices for e.g. utilities and auxiliary expenses for employees vary. The last term of the objective denotes the relocation costs between facilities and between the hub and facilities. Relocations are necessary to install modular plants at each facility initially and to adapt the production network in future time periods. Parameter $c_{ii'}^{reloc}$ denotes the costs of relocating a modular plant from facility i to facility i'. If modular plants are relocated between production facilities, the costs of dismounting and mounting the modular plant are included. Furthermore, the transportation costs of modular plants between facility i and i' are included based on the road distance between the two facilities. Constraint (2) ensures all customer demand D_{int} is met by shipments from production facilities. Constraint (3) requires that the shipments of each facility do not exceed the production quantity. The production quantity is limited by the capacity provided by modular plants installed at each facility [Constraint (4)]. Parameter Cap_{gp}^{prod} specifies the maximum production quantity of a modular plant of type g for product p.

The maximum amount of base polymers that a supplier can provide per period is defined as Cap_s^{raw} . Constraint (5) ensures that the capacity limit is not violated. Constraints (6) and (7) require that sufficient base polymers and additives are available at each production facility. In our case, the final product consists of 98% base polymers and 2% additives, i.e. $f^{bp} = 0.98$ and $f^{add} = 0.02$.

Production capacities can be installed by relocating modular plants either from the modular hub (i = 0) or another facility. However, to establish initial capacities in the first time period, modular plants have to be shipped to facilities from the modular hub in time period t = 0. As modular plants can be relocated between facilities, the number of modular plants installed at each facility is captured by Constraint (8). If the number of modular plants deviates from one period to another, the difference has to be met by relocations. The number of modular plants m at facility i in period t is modeled as a binary variable. To obtain the difference of the number of modular plants available in period t compared to t - 1, the binary variables in Constraint (8) are multiplied with m_1 and m_2 , respectively. Since relocations are modeled with an integer variable, the right hand side of Constraint (8) denotes the number of relocations from and to the respective facility. Relocated modular plants are available at the destination facility in the next period.

Constraint (9) ensures that only one capacity level may be selected, which denotes the number of modular plants installed at each location in each period. We assume that there is no production at the hub i = 0. In period t = 0, there is no demand and variable y_{0gm0} determines the number of modular plants that are prepared for production and deployed to the network from the modular hub [Constraints (10)–(13)]. Constraints (11) ensures that a production facility has to be open to operate modular plants. There are operational costs for each time period a facility is open, and we assume that a facility has to operate throughout the planning horizon after it has been opened [Constraints (12)]. Initially, there are costs for the installation of modular plants at production facilities and for transport from the modular hub. Modular plants may be relocated at the beginning of each period. For a relocation, modular plants are dismounted at the current facility, loaded onto a truck and transported to the next facility at which they can be mounted again. Finally, Constraints (14)–(17) specify the domains of the decision variables. In the initial state of the production network, no production facility is active and no modular plants are operated.

4.3 Experimental setting and scenarios

This section details our experimental setting for the case study and describes the construction of our scenarios. The specialty chemical company considered in our case study has a central production site for base polymers in central Europe that is able to provide base polymers for the decentral production facilities. This facility serves as the modular hub i = 0, and, in the basic scenario, it is the only supplier of base polymers *s*. Our customer data represent the customers of the chemical company that sells the specialty we are considering. For the case study, a number of 100 customer locations were selected from the data. Multiple orders are considered per customer and each order may span a single or multiple planning periods. Furthermore, a number of 100 potential facilities for modular production were selected. Figure 4 shows the locations of customers and potential facilities.

The distances between facilities and customers, in-between facilities as well as between suppliers and facilities were obtained as street distances from the *Google Directions* service. The operating costs of each facility are largely defined by the costs of four full-time employees needed for logistics and production monitoring. Some cost parameters are only known for conventional batch production with largescale production systems. To estimate the cost parameters for a modular production process, we have conducted expert interviews with supply chain managers from the chemical industry.



Fig. 4 Overview of the locations of customers and potential facilities and local suppliers

We construct scenarios for our case study on the basis of three aspects related to the economic benefits of small-scale modular plants. A basic scenario of small-scale modular production serves as a base line for comparison with the other scenarios which consider additional opportunities. These may lead to particular benefits in combination with modularization.

As discussed in Sect. 3.3, modular plants consist of base polymer and additive tanks, a production container and a cleaning container. Small-scale modular plants can be assembled quickly and the costs of the required equipment are low due to the moderate level of technical complexity. Due to different viscosities, the processing of each base polymer requires a different static mixer. Two different plant layouts facilitated by two different container designs are compared: In the basic scenario, there is a specialized layout with a high capacity static mixer, here called mono process (\mathbf{M}) , for products based on a single base polymer. Thus, each modular plant is equipped with a single process line with a capacity of 3000 t per month. In this case, there are three possible modular plant configurations, i.e. $G = \{1, 2, 3\}$, with a direct correspondence to the three product families. Additionally, a more flexible layout with three parallel (P) lower capacity static mixers is considered so that in this case any base polymer can be processed. The latter case allows for a greater product flexibility of each modular plant. In case of the flexible layout, we assume that the capacity for each base polymer and product family is a third of the capacity of the mono product mixer, i.e. 1000 t. Thus, there is only a single modular plant configuration $(G = \{1\})$, which provides capacities for all product families. In addition to modifying the set of configurations G, we adjust parameter Cap_{gp}^{prod} . Without product flexibility, there is only one nonzero value Cap_{gp}^{prod} for each configuration g, as each configuration is specialized for a single product family p. If product flexibility is considered, then Cap_{1p}^{prod} is 1000 t for all products.

At present, the personnel requirement at each facility accounts for a large part of the fixed costs of the production network. In the following, this is referred to as normally staffed production (**S**). In combination with modular production, there is the option of switching to autonomous production (**A**). In case of autonomous production, the operational cost of production facilities are reduced due to the lower need for human resources. At the same time, the investment cost per modular plant are increased because of the more complex control system. We adapt the parameters of our mathematical formulation by reducing the operational cost of facilities (c_i^{loc}) and increasing the investment cost per modular plant, we use a factor of 1.55 for the investment costs, which include equipment and assembly (Brown 2016).

The operation of modular plants at decentral facilities allows the use of local sourcing options. Despite efficient FTL transport, the logistics costs of the base polymers constitute a major share of total costs. Therefore, scenarios with central (\mathbf{C}) and with local (\mathbf{L}) sourcing options are compared to quantify the benefit of local sourcing. A number of 20 suppliers that can provide the relevant base polymer were identified (see Fig. 4). To apply our model to the case of local sourcing, we extend the set of suppliers *S*. Local sourcing is not allowed for additives, since the exact mixture of additives involves important know-how. Therefore, all

	-					,		
Scenario	MSC	PSC	MAC	PAC	MSL	PSL	MAL	PAL
Mono production	1		1		1		1	
Parallel production		1		1		1		1
Staffed production	1	1			1	1		
Autonomous production			1	1			1	1
Central sourcing	1	1	1	1				
Local sourcing					1	1	1	1

Table 2 Overview of case study scenarios (bold letters used as scenario identifier)



Fig. 5 Comparison of total production network cost across the scenario set

additives are delivered from the facility at which a modular hub has been established. The set of scenarios that results for our case study from the combination of production and sourcing alternatives is shown in Table 2.

5 Results and implications

In this section, the differences in costs and network structures among the eight scenarios are discussed. All scenarios were implemented in *Python 3* and solved to optimality with *Gurobi 9.0*. The run times ranged from 408.81 s for scenario PAL to 10,099.68 s for scenario MSC with a mean run time of 3331.73 s. For each scenario, the structure and cost of the production network are discussed to derive recommendations for the design of modular production networks. In our discussion, we refer to the link between facility and customers as arc. For simplicity, we also plot arcs in the visualizations of our production network instead of the actual street route.



Mono, Staffed production and Central sourcing

Fig. 6 Overview of the production network structure in scenario MSC



Parallel, Staffed production and Central sourcing

Fig. 7 Overview of the production network structure in scenario PSC

The total cost of the production network over the course of the planning horizon of one year is shown in Fig. 5. The detailed costs are specified in the Appendix (see Table 3). It is apparent that the introduction of parallel process lines, autonomous production technology and/or local sourcing decisions have reduced the total cost in each case.

In the following, the exact causes and implications of the solution structure are examined. Excerpts of the production network structure for all scenarios are shown



Mono, Autonomous production and Central sourcing

Fig. 8 Overview of the production network structure in scenario MAC



Parallel, Autonomous production and Central sourcing

Fig. 9 Overview of the production network structure in scenario PAC

in Figs. 6, 7, 8, 9, 10, 11, 12 and 13. Each map shows all facilities that are activated over the planning horizon, customer demand proportional to circle size and all transportation arcs used to serve product demand. It is evident from the data in Fig. 5 that the cost reduction obtained by autonomous production facilities is more than twice as high compared to parallel process lines for both the case of central sourcing (scenarios *C) and local sourcing (scenarios *L).

Furthermore, it can be noted that there are synergy effects when both autonomous production facilities and parallel process lines are considered together. The value



 \mathbf{M} ono, \mathbf{S} taffed production and \mathbf{L} ocal sourcing

Fig. 10 Overview of the production network structure in scenario MSL



Parallel, Staffed production and Local sourcing

Fig. 11 Overview of the production network structure in scenario PSL

of the combination of both flexibility options is higher than the sum of both values of the respective individual advantages. This is valid independent of the sourcing decision. In general, the value of autonomous production and parallel process lines is largely similar in case of central and local sourcing. It is slightly higher when local sourcing options are available, since more flexibility also allows to adjust the production network more efficiently with respect to the supplier locations. This enables an efficient integration of local sourcing options. However, a certain trade-off



Mono, Autonomous production and Local sourcing

Fig. 12 Overview of the production network structure in scenario MAL



Parallel, Autonomous production and Local sourcing

Fig. 13 Overview of the production network structure in scenario PAL

between proximity to the supplier and customer is evident. This is reflected by an increase of sourcing costs when providing more flexibility options. In the following, a more detailed analysis is presented for each of the scenarios.

5.1 Central sourcing

As seen in Fig. 6, a number of 9 geographically dispersed production facilities are activated during the planning horizon in the central sourcing scenario. In total, 27

modular plants are deployed to the production facilities. Every production facility is equipped with exactly one modular plant of each configuration.

Even though there is only a single source available for raw materials (see Fig. 4) in this scenario, the costs that can be saved by production near to customers outweigh the costs of facility operation. By transporting raw materials to each production facility in bulk, the shipping distance of finished products is reduced. Scenario MSC with three separate types of modular plants for each base polymer and normally staffed production facilities has the highest cost across the scenario set. Almost half of the total cost are delivery costs for finished products. The average delivery distance is 495 km. Many customer deliveries have to cover a long distance which is also evident from the long arcs in Fig. 6. The personnel costs at each facility account for an important part of the total cost, which leads to long delivery distances, especially for customers with small orders. Overall, the costs of logistics for raw material handling and delivery of finished products are predominant.

Scenario PSC considers a different design of modular plants where each production container is equipped with three parallel production lines. The capacity of each production container is decreased, but every production container can process each of the base polymers. In comparison to scenario MSC, the cost are reduced by EUR 1.67 million. Eleven facilities are activated over the planning horizon, and a single flexible modular plant is deployed at each (see Fig. 7). It is sufficient to operate a single modular plant at a facility to serve the customer demand for all base polymer types. The average delivery distance is 423 km. A large part of cost savings can be explained by reduced delivery costs. Parallel production allows customers to be always served by the closest facility, independent of the specific product they require. In the mixing process under consideration, the capacity of the modular plants is often not fully utilized even if it is split into three parallel process lines. This can be explained by the high attainable throughput of a mixing process in continuous operation.

Alternatively, scenario MAC considers production facilities that are autonomously operated and thus require less personnel. An autonomous operation of production facilities enables an even greater cost reduction in comparison to parallel production. A large fraction of these savings is achieved because no personnel costs are incurred for the operation of decentralized facilities. Outstanding is the number of 15 production facilities and 34 modular plants in operation which strongly increases compared to scenarios MSC and PSC (see Fig. 8). This leads to an increase in sourcing costs, because facilities tend to be closer to the customers. The increase is, however, offset by a reduction of delivery and facility operation costs. The average delivery distance is reduced to 380 km, since it is now favorable to operate more decentral facilities. Yet, the difference of the production network structure between scenarios PSC and MAC is remarkable. The number of modular plants in use is more than three times as high in scenario MAC compared to scenario PSC, even though the direct operational costs of modular plants remain unchanged.

Scenario PAC combines parallel production with autonomous production facilities. The optimal solution reduces the cost by EUR 5.59 million compared to the base scenario MSC. Further savings are mainly realized by the additional reduction of delivery costs. In the production network, a number of 18 different production facilities is activated and a single modular plant is deployed to each (see Fig. 9). The average delivery distance is reduced to 355 km.

5.2 Local sourcing

In this section, the results of scenarios that allow for local sourcing of base polymers are discussed. The cost of scenario MSL with local sourcing options is EUR 6.47 million lower in comparison to the base case MSC. The number of modular plants and facilities increases to 30 production modules and 10 production facilities, such that each product family can be produced at every production facility. Most savings result from the sourcing costs for base polymers. Figure 10 shows that many production facilities are now selected in close proximity to local sources of polymers. The average delivery distance is reduced to 479 km.

In scenario PSL, parallel production is considered additionally to local sourcing options. Further savings of EUR 1.74 million are obtained. A number of 11 production facilities are activated with a single modular plant each (see Fig. 11). The savings are mainly caused by two factors. First, the average delivery distance is reduced to 446 km as customers are generally served from the nearest production facility. Second, the module operational costs are lower since less modular plants are required. There does not seem to be much additional synergy from the combination of local sourcing options, as the savings of EUR 1.74 million are similar to the savings of EUR 1.67 million achieved in the case of parallel production and central sourcing.

If autonomous production facilities are combined with local sourcing options, again the cost reduction is significantly higher in comparison to parallel process lines. Compared to the scenario with local sourcing only, the cost are reduced by EUR 3.53 million. A number of 38 modular plants are operated at 18 different production facilities (see Fig. 12). As the average delivery distance is reduced to 385 km, a large part of the savings is obtained from the delivery costs. Similarly to scenario PSC, which considers central sourcing, the number of modular plants increases significantly, although the operational costs only change implicitly due to the operational costs of each production facility. Examining the network structure, it is apparent that many long transportation arcs between production facility and customers are avoided by operating more facilities and more modular plants of each type.

Finally, scenario PAC combines parallel production, autonomous production facilities and local sourcing options. It results into the lowest overall total cost of EUR 22.97 million. Over the planning horizon, 19 different production facilities are activated and 19 modular plants are deployed. The total cost are reduced by more than a third in comparison to the base case (Fig. 13).

5.3 Implications

The optimal consideration of all three additional opportunities offered by smallscale modular production results in the supply chain design with the lowest cost, with a reduction of costs by more than a third compared to the base scenario. In particular, the consideration of local sourcing options greatly reduces the costs of raw material handling. Due to the importance of these costs for the type of production process we consider, there is a large impact on total cost for all scenarios. Furthermore, it can be seen that local sourcing options greatly change the structure of the small-scale modular plant production network. Production facilities tend to be frequently activated in proximity to local sources. If a large part of the end product consists of widely used raw materials, it is advisable to evaluate the implementation of modular production in combination with local sourcing. The savings must, however, be weighed against the profit that may be generated from the central selfproduction of this raw material.

In case of a mixing process for specialty chemicals production, it is clearly preferable to install parallel process lines for different product families, each with lower capacity, rather than to operate a single process line per plant with large capacity. Even the reduced capacity of parallel process lines is rarely exhausted in this case study, as a continuous mixing process such as the one under consideration can achieve a high throughput.

Interestingly, there is only a moderate level of synergy between the availability of autonomous production facilities and parallel production. Autonomous production facilities enable the operation of a large number of production facilities that are very close to each customer. It allows for a reduction of the costs of human resources which make up a large fraction of the operational costs of decentral facilities. Most facilities only operate a single modular plant, but their position is strategically chosen to fulfill orders of the specific product family. With parallel production, it is possible to reduce the costs of facility operation and module operation while a lower number of facilities still manages to serve most customers within a reasonable distance. Thus, both options support shorter delivery distances.

However, beyond a certain point shorter delivery distances also imply a longer distance to sources. Looking at Fig. 5, it can be seen that the sourcing costs rise with increasing flexibility. The scenarios with most flexibility for the case of central and local sourcing (PAC and PAL) are also associated with the highest sourcing costs. This effect reduces potential synergies with a rising level of flexibility. Figure 14 shows the delivery distances for each scenario. Scenario MSC and MSL exhibit a high volume of deliveries that have to be transported over long distances. Overall, it is apparent that in both the case of central and local sourcing, large reductions of the delivery distances are possible and the efficiency of the production network can be greatly increased.

6 Conclusion and outlook

This paper has shown that there are important synergies between modular production concepts and local sourcing. At the same time, it is crucial to select an appropriate technical design for the modular production system. We have presented a new mathematical formulation for the optimization of modular production networks in the specialty chemical industry. The model uses a new type of



Fig. 14 Comparison of distances of deliveries across the scenario set

constraint for modeling relocations, allowing it to be optimally solved for several scenarios. In comparison to the general formulations from Becker et al. (2019), the new mathematical formulation has allowed us to solve problem instances with a higher number of production facilities. To create realistic scenarios for our case study, the scenarios are based on real data from the chemical industry. An example of the individual production of special polymers on the basis of few base polymers has been investigated. Results show that the cost highly depend on both the sourcing pattern and the technical design of the modular production system. The location flexibility of modular production plants allows for a decentral operation and thus local sourcing options ought to be taken into account. If local sourcing options are used, it is often possible to reduce the distance to both suppliers and customers by the appropriate placement of the production facilities. An autonomous operation of the production facilities and flexible processes also lead to a substantial reduction of the delivery distance and the production network cost. As a result, shorter delivery distances can also improve the CO_2 balance of the production network. These two options for the technical design can reduce the operational costs for each production facility or the costs for the modular plants in use. If the production of base polymers is part of the core business of a company, local sourcing options may not be viable because they are associated with the loss of the profit margin for base polymers. However, our case study has shown that both autonomous production facilities and flexible production processes can already lead to a more efficient production network.

Our findings extend and confirm previous results. In comparison to Becker et al. (2019), we provide a more detailed analysis of a specific economic case, in

particular quantifying the value of local sourcing options. The case at hand does not require plant reconfigurations, as there is only a limited set of configurations.

We find that modular plants are only rarely relocated between production facilities and the value of relocations is low, too. This is in line with the findings of Becker et al. (2018a, 2019), in which the value of modular plant relocations between production facilities is low.

In the future, it will be important to ensure the technical compatibility between apparatuses to support plug-and-produce in the context of modular production. For a broader applicability, new concepts for small-scale apparatuses are required for a wide range of process steps. In our case study, we have evaluated two different process layouts for modular plants. Even more different sizes are conceivable based on the specific area of application. Thus, another possible area of future research would be to use the proposed mathematical formulation to determine the suitable size of capacity modules for engineering. This facilitates the design of modular plants according to the actual requirements of the market situation. Further research could also evaluate the financial impact of collaborations between companies associated with modular production networks. For instance, we have assumed long-term leasing contracts for facilities in our case; also, flexible short-term leasing contracts could additionally promote the locational flexibility of modular plants. Furthermore, different companies could be responsible for the construction of modular plants and operation of a modular production network, opening up the possibility for new business models.

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Scenario	MSC	PSC	MAC	PAC	MSL	PSL	MAL	PAL
Sourcing cost (M€)	8.81	10.02	10.22	10.43	2.23	2.74	3.45	3.78
Delivery cost (M€)	15.68	13.41	12.63	11.28	15.19	14.15	12.22	10.99
Production cost (M€)	5.28	5.28	5.28	5.28	5.28	5.28	5.28	5.28
Module operation (M€)	1.60	0.66	2.07	1.07	1.77	0.66	2.23	1.13
Module investment (M€)	0.32	0.17	0.52	0.34	0.36	0.17	0.57	0.36
Facility operation (M€)	3.24	3.96	0.90	1.07	3.60	3.96	1.00	1.13
Relocation cost (M€)	0.40	0.16	0.53	0.27	0.43	0.16	0.58	0.30
Total cost (M€)	35.33	33.66	32.15	29.74	28.86	27.12	25.33	22.97
Average arc length (km)	495	423	398	355	479	446	385	347

 Table 3
 Comparison of costs in the different scenarios

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Appendix

References

- Becker T, Lier S, Werners B (2018a) Tactical planning of modular production networks with reconfigurable plants. In: Kliewer N, Ehmke JF, Borndörfer R (eds) Operations research proceedings 2017. Springer International Publishing, Cham, pp 549–555. https://doi.org/10.1007/978-3-319-89920 -6_73
- Becker T, Lutter P, Lier S, Werners B (2018b) Optimization of modular production networks considering demand uncertainties. In: Fink A, Fügenschuh A, Geiger MJ (eds) Operations research proceedings 2016. Springer International Publishing, Cham, pp 413–418. https://doi.org/10.1007/978-3-319-55702-1_55
- Becker T, Lier S, Werners B (2019) Value of modular production concepts in future chemical industry production networks. Eur J Oper Res. https://doi.org/10.1016/j.ejor.2019.01.066
- Bieringer T, Buchholz S, Kockmann N (2013) Future production concepts in the chemical industry: modular-small-scale-continuous. Chem Eng Technol 36(6):900–910. https://doi.org/10.1002/ ceat.201200631
- Brown T (2016) Engineering economics and economic design for process engineers. CRC Press, Boca Raton. https://doi.org/10.1201/b15877
- Buchholz S (2010) Future manufacturing approaches in the chemical and pharmaceutical industry. Chem Eng Process Process Intensif 49(10):993–995. https://doi.org/10.1016/j.cep.2010.08.010
- Ekici A (2013) An improved model for supplier selection under capacity constraint and multiple criteria. Int J Prod Econ 141(2):574–581. https://doi.org/10.1016/j.ijpe.2012.09.01
- Esmaeilikia M, Fahimnia B, Sarkis J, Govindan K, Kumar A, Mo J (2016) Tactical supply chain planning models with inherent flexibility: definition and review. Ann Oper Res 244(2):407–427. https://doi. org/10.1007/s10479-014-1544-3
- European Commission (2014) Final report for flexible, fast and future production processes. Technical report
- Ferrio J, Wassick J (2008) Chemical supply chain network optimization. Comput Chem Eng 32(11):2481– 2504. https://doi.org/10.1016/j.compchemeng.2007.09.002
- Hady Ł, Wozny G (2012) Multikriterielle Aspekte der Modularisierung bei der Planung verfahrenstechnischer Anlagen. Chemie-Ingenieur-Technik 84(5):597–614. https://doi.org/10.1002/cite.201100175
- Hein F, Almeder C (2016) Quantitative insights into the integrated supply vehicle routing and production planning problem. Int J Prod Econ 177:66–76. https://doi.org/10.1016/j.ijpe.2016.04.014
- Hsu CI, Li HC (2009) An integrated plant capacity and production planning model for high-tech manufacturing firms with economies of scale. Int J Prod Econ 118(2):486–500. https://doi.org/10.1016/j. ijpe.2008.09.015
- Jena SD, Cordeau JF, Gendron B (2015) Dynamic facility location with generalized modular capacities. Transp Sci 49(3):484–499. https://doi.org/10.1287/trsc.2014.0575
- Kaczmarek S, Mosblech C, Lier S, ten Hompel M (2015) Modularisierung und automatische Anordnungsplanung der Intralogistik f
 ür modulare Containeranlagen in der Prozessindustrie. Chemie Ingenieur Technik 87(9):1246–1257. https://doi.org/10.1002/cite.201400160
- Kadipasaoglu S, Captain J, James M (2008) Polymer supply chain management. Int J Logist Syst Manag 4(2):233–253. https://doi.org/10.1504/IJLSM.2008.016573
- Lang J, Stenger F, Richert H (2011) Small is beautiful. Evonik Elem 37:12-17

- Lier S, Wörsdörfer D, Gesing J (2013) Business models and product service systems for transformable, modular plants in the chemical process industry. In: Product-service integration for sustainable solutions. Springer, Berlin, pp 227–238. https://doi.org/10.1007/978-3-642-30820-8_20
- Martínez-Costa C, Mas-Machuca M, Benedito E, Corominas A (2014) A review of mathematical programming models for strategic capacity planning in manufacturing. Int J Prod Econ 153:66–85. https://doi.org/10.1016/j.ijpe.2014.03.011
- Melo MT, Nickel S, da Gama FS (2006) Dynamic multi-commodity capacitated facility location: a mathematical modeling framework for strategic supply chain planning. Comput Oper Res 33(1):181–208
- Melo MT, Nickel S, Saldanha-da Gama F (2009) Facility location and supply chain management—a review. Eur J Oper Res 196(2):401–412. https://doi.org/10.1016/j.ejor.2008.05.007
- Rauch J (2006) Multiproduct plants. Wiley-VCH, Weinheim
- Seifert T, Sievers S, Bramsiepe C, Schembecker G (2012) Small scale, modular and continuous: a new approach in plant design. Chem Eng Process Process Intensif 52:140–150. https://doi.org/10.1016/j. cep.2011.10.007
- Shah N (2005) Process industry supply chains: advances and challenges. Comput Chem Eng 29(6):1225– 1235. https://doi.org/10.1016/j.compchemeng.2005.02.023
- Tsiakis P, Papageorgiou LG (2008) Optimal production allocation and distribution supply chain networks. Int J Prod Econ 111(2):468–483. https://doi.org/10.1016/j.ijpe.2007.02.035
- Wörsdörfer D, Lier S, Grünewald M (2016) Characterization model for innovative plant designs in the process industry—an application to transformable plants. Chem Eng Process Process Intensif 100:1–18. https://doi.org/10.1016/j.cep.2015.11.004

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