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PRODUCTION MANAGEMENT

Product allocation and network configuration in global production networks

An integrated optimization approach

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Abstract
Driven by an increasing demand for individualized products and shorter product life-cycles, companies continuously extend their product portfolio. Simultaneously, companies expand into new markets to reach customers and to exploit varying location factors to reduce costs. Global production networks (GPNs) have to be adapted constantly to react to new circumstances and changes in the demand of products. To remain competitive, product allocation and production network configuration are essential. At the same time, companies face an increasing complexity while handling these tasks. This poses a challenge particularly for small and medium sized companies, which have limited planning capacities and management resources. Current literature describes optimization-based approaches for the integrated product allocation and network configuration of production networks. Yet, multi-objective models lack transparency of results and user friendliness. Therefore, this paper presents a multi-objective optimization model that incorporates flexibility and reconfiguration aspects to determine an optimal product allocation and network configuration of a GPN over a given planning horizon. The preemptive goal programming approach is used to identify Pareto-optimal solutions and to increase user friendliness. The subsequent verification, validation and post-optimality analysis combined in a structured process enables a wide range of companies to apply the approach. The model is successfully applied in the GPN of a special machine manufacturer, which produces high precision metrology machines. Due to its transparent approach for complex planning problems, the developed method provides a solid base for well-founded, objective decisions. Hence, the risk of costly errors in the planning phase is reduced.

Keywords Global production networks · Multi-objective optimization · Decision making · Product allocation · Network configuration · Post-optimal analysis

1 Introduction

Due to new markets in emerging countries, an increasing globalization of manufacturing companies can be observed [1]. Companies of all sizes nowadays typically operate in global production networks (GPNs) [2] to meet differing market requirements [3, 4] as well as to counter the cost pressure from new competitors in developing markets by utilizing varying location factor characteristics [5]. GPNs are understood as dynamic, open and overlapping systems. They are structured by dense networks of interconnected actors. These globally distributed and interconnected networks of different facilities enable, among other things, cost advantages, the adaptation of products to local requirements and targeted access to labour or resources [2]. Furthermore, almost 80% of global trade are referable to GPNs [6]. Therefore, GPNs are nowadays indispensable as a structure of value creation in a global context. Due to unexpected changes in the complex environment of GPNs, it is required to constantly adapt to changing conditions such as demand shifts, labor cost or access to resources [2]. This leads to complex challenges in GPNs, e.g., when allocating products to production network entities while utilizing and adapting capacities and structures of GPNs [7, 8].

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Small- and medium-sized enterprises (SMEs) take an essential role in the German manufacturing sector. In order to manufacture products close to the market and locally adapted, to gain a competitive advantage in production and procurement cost, and to achieve access to local knowledge and skills, SMEs have established production sites worldwide [2, 5]. At the same time, limited planning and management resources as well as missing experience in the use of decision support systems lead to high uncertainties in the planning and management of GPNs for SMEs [9]. Due to their high investment effort and long-term nature, configuration and allocation decision are only reversible at great expense [5]. Moreover, allocating products to GPN entities while readjusting global production capacities and capabilities represent a highly complex task for SMEs. To counteract these aspects and increase planning reliability, decision support systems are necessary to identify further potential for improvements [10]. Decision support systems like simulation or optimization models are currently rarely used because of missing knowledge about the potential use as well as high complexity of such models [11].

The aim of this paper is therefore to develop a multi-objective optimization model for GPNs facilitating the integrated configuration adaption and the allocation of product variants to network entities. By means of an user-friendly implementation and user guide as well as transparent visualization of results, the approach is especially designed to be applicable in SMEs.

The remainder of this paper is organized as follows: Section 2 provides a brief summary of the literature. Section 3 presents the multi-objective optimization model. In Sect. 4, the real-life application using data from a special machine manufacturer and the discussion of results are presented. Section 5 completes with a conclusion.

2 Related work

Based on the objective of the work, the requirements for an integrated approach for product allocation and network configuration in GPNs are defined and specified. Based on the identified criteria, the preliminary work and approaches in the fields of the product allocation in GPNs and the optimization of the network configuration are narrowed down. Subsequently, the approaches are discussed and the remaining research deficit is derived.

2.1 Characteristic requirements

In accordance with Hochdoerffer et al. [10] and Martínez-Costa et al. [12], eight criteria are derived. These can be categorized into the three categories modelling, scope of action and optimization (cf. Table 1). The first two criteria focus on the modeling of the system. In many practice-related allocation problems and questions concerning the optimal design of the production network, different and conflicting objectives need to be considered [13]. Therefore a multi-criteria formulation of the target system is necessary. To enable differentiation between production processes and resources as well as the depth of value added, a multi-level modeling of the production process is required [14]. In order to be able to react dynamically to changing customer demand or changes in the corporate environment and thus operate economically, it is important to enable a dynamic reconfigurability of the production network [15]. This allows the planning horizon to be adjusted based on the ability of a network to discretely adjust its as-is configuration [10]. Therefore it is also mandatory to allow dynamic changes in the network routing flexibility, product mix flexibility and volume flexibility [16] For the acceptance of optimisation models it's important to guarantee the comprehensibility of the determined solution [11]. On the one hand, comprehensibly presented solutions are important for creating acceptance and transparency; on the other hand, there is a need for a user friendly interface that makes regular use of the developed methodology possible [17].

2.2 Assessment of existing approaches

Multiple approaches focusing on product allocation, production network configuration and the combination of both objectives exist. As indicated in Table 1, the selected state of the art literature has comprehensively been reviewed regarding the specified criteria.

The multitude of approaches indicates that mathematical modeling of planning problems is an established form of decision support for allocation and network configuration problems. Often, however, the establishment of a multi-objective system is renounced due to the increasing complexity of the model (e.g., [17, 18]). From the considered approaches, Lanza and Moser [19] describe such a multi criteria target system most comprehensively. Models considering multi-stage production processes show differences as well. Hochdoerffer et al. [10] allow the user to define the value creation levels, whereas Paquet et al. [18] specify process steps in detail. Routing flexibility is at least partially considered in all presented approaches. Restrictions on routing flexibility can be found, for example, in the model of Fleischmann et al. [17], in which a pre-specified allocation table of products limits the choice of the path of a product through the network. Volume flexibility, on the one hand, is neglected by many publications (e.g., [20, 21]). The integrated model of Hochdoerffer et. al 2021 [10] can be highlighted by its extensive consideration of volume flexibility, but didn't include a multi criteria target system. The determined solution is difficult to comprehend in many of the

Table 1 Overview: approaches to the design of global production networks using mathematical optimization models

	Modelling		Scope of action				Optimization	
	Multi-criteria target system	Multi-stage modeling of the production process	Dynamic reconfigurability	Routing flexibility	Product mix flexibility	Volume flexibility	Comprehensibility of the determined solution	User-friendliness
Product allocation models								
Inman and Gonsalvez [23]	◑	◔	◔	●	◑	◑		
Lin et al. [24]		◕	◑	◑	◑		◔	◔
Wittek et al. [25]			◕	◑	●	◑		
Wittek [8]			●	◑	●	◑	◔	◔
Ziegler et al. [20]		◕		◕	◕			
Network configuration models								
Guillén et al. [26]	●	◔	◔	◔	◔		◔	◔
Thanh et al. [27]		●	●	◑	◔	◑		
Lanza and Moser [19]	●	●	●	◑	◑		◔	◔
Integrated product allocation and network configuration models								
Bhutta et al. [28]			●	●	●	◔		
Levis and Papageorgiou [29]			●	◑	◕	◑		
Fleischmann et al. [17]		●	●	◑	●	◕		
Paquet et al. (2008) [18]		●	●	●	●	●	◔	
Bihlmaier et al. (2009) [30]		●	◔	◑	◑	●	◔	
Kauder and Meyr [7]		●	●	●	●	●		
Kohler [31]		●	●	◑	◑		◑	
You et al. [21]			●	◑	◑			
Liu and Papageorgiou [13]	●		●	●	●	◑		
Huang and Goetschalckx [32]		◔		◕	◕		◔	◔
Mariel and Minner [33]		◑	●	●	●	◑		
Mariel and Minner [34]		◑	◑	●	●			
Srinivasan and Khan [35]		●	◑	●	◕		◔	
Léon-Olivares et al. [22]				●	◑		◔	
Hochdoerffer (2021) [10]		●	●	●	●	●	●	◕

Harvey ball fill level: criterion not considered (empty cell) → considered comprehensively (●)

scientific papers. Often, scenario techniques or sensitivity analyses are used to provide deeper insights into the solution finding process (e.g., [22]). Most models are implemented in a special operations research software, which is difficult or impossible to be used by non-professionals. Some publications discuss the development of user interfaces without referring to it in detail (e.g., [17]) This assessment of the mentioned approaches shows that so far no approach fulfills the requirements completely. The novelty of the paper thus lies in the development and validation of an user-friendly optimization model including post-optimality analyses, which are currently rarely used due to a deficit of knowledge. Furthermore the focus should be set to SMEs with a make-to-order or engineer-to-order production strategy.

3 Multi-objective optimization model for global production networks

In the following, the multi-objective optimization model for the integrated configuration of GPNs and product allocation is presented.

3.1 Overview

The optimization model on the one hand considers the internal company network with personnel resources, plants and transportation connections. On the other hand, the customer and supplier sides are also included in the evaluation process in order to ensure a holistic, integrated optimization of all decision-relevant processes.

The proposed model takes into account a flexible set of planning periods as well as the initial state of the production network. Plants can be opened and closed at previously defined locations in the planning horizon. The production process is split into segments at which the course of value creation cannot be spatially left. Therefore, segments can represent assembly lines or individual assembly stations. The model focuses on use cases in which predominantly manual assembly processes occur and workers are considered strategic resources. Substitutable resources with comparable qualifications (possible plant-segment-product combinations) are combined into personnel groups to reduce model complexity.

Production segments and personnel resources are assigned to each plant in the GPN. The configuration of segments and personnel can be reset for current and future end products. Demand nodes represent customers and require end products. A deterministic demand is assumed. The GPN operates in a make-to-order or engineer-to-order context, so it is not necessary to consider significant warehouses in the GPN. Supplier nodes are considered for material and components which are procured externally.

Since this paper's main focus is to present flexibility and reconfiguration aspects in GPNs the following section describes these adaptation aspects in detail. The basic material flows, capacity restrictions, personnel and segment allocation in the GPN can be found in Appendix 1.

3.2 Adaptation aspects

In these section, flexibility and reconfigurability aspects of the GPN are addressed and incorporated into the model.

Table 2 Additional sets for the extension of the basic model

Set	Description
$E \subset N$	Potential external units
$E_p \subset E$	External units that can provide the product state $p(p \in C)$
ZYK	Periods t before the start of a new cycle

Table 3 Additional indices for extension of the basic model

Index	Description
$e \in E$	External unit
$zyk \in ZYK$	Periods t before the start of a new cycle

To make the model applicable for use cases where a production network is already in place, brownfield planning and additional strategic decisions in advance of planning will be implemented.

All quantities, indices, decision variables and functional parameters introduced in addition to the basic model (Appendix 1) can be found with respective explanations in Tables 2, 3, 4 and 5.

3.2.1 Flexibility aspects

Building a flexible GPN is a strategic task. Product-mix and routing flexibility are already part of the basic model. In the following, this basic model is extended to include aspects of volume flexibility of internal and external units.

Flextime As an instrument for the flexibility of personnel resources, flextime FT_{urt} is used across industries [36]. To simplify the equations it is assumed that the upper and lower bounds for flextime are identical in amount and Eq. 1) is set up accordingly.

$$|FT_{urt}| \leq fTMax_{ur} \cdot AnzR_{urt} \, \forall u \in U, r \in R, t \in T \tag{1}$$

Following [36], flextime is regulated per period *per* (e.g., month) and per cycle *zyk* (e.g., year). Equation 2 sets an upper limit for the use of flextime in a cycle.

It is assumed that overtime accumulated at the end of the cycle is paid out to employees. Negative flextime is compensated at the end of a cycle in the focal company. Therefore, the Eq. 3 applies to the model.

Table 4 Additional decision variables for the extension of the basic model

Decision variables	Description
A_{eupt}	Number of units of product $p(p \in C)$ transported from external unit $e(e \in E_p)$ to plant $u(u \in U)$ in period $t(t \in T)$
$AnzRAdp_{urt}^{+/-}$	Number of natural resources $r(r \in R)$ in plant $u(u \in U)$ hired $^{(+)}$ or fired $^{(-)}$ in period $t(t \in T)$
$AnzShift_{ust}$	Number of shifts on segment $s(s \in S_u)$ in plant $u(u \in U)$ in period $t(t \in T)$
FT_{rt}	Used flextime from resource group $r(r \in R)$ in plant $u(u \in U)$ in period $t(t \in T)$
$SAct_{ust}$	Status of segment $s(s \in S_u)$ in plant $u(u \in U)$ in time period $t(t \in T)$. Takes the value 1 for segment open and 0 for segment closed
$SAdp_{ust}^{+/-}$	Status whether the segment $s(s \in S_u)$ in plant $u(u \in U)$ in time period $t(t \in T)$ is opened or closed. Takes the value 1 if the action occurs before the start of the period, 0 otherwise
$UAct_{ut}$	Status of the plant $u(u \in U)$ in time period $t(t \in T)$. Takes the value 1 for plant open and 0 for plant closed.
$UAdp_{ut}^{+/-}$	Status whether the plant $u(u \in U)$ is opened or closed in time period $t(t \in T)$. Takes the value 1 in each case if the action occurs before the start of the period, 0 otherwise

Table 5 Additional functional parameters for extension of the basic model

Parameter	Description
$capE_{ep}^{e}$	Capacity upper bound of external unit $e(e \in E_p)$ for product $p(p \in C)$
$closeU_u$	Fixed time $t(t \in T)$ at which plant $u(u \in U)$ should be closed
$fTMax_{ur}$	Upper limit for the use of flextime of resource group $r(r \in R)$ in plant $u(u \in U)$
$fTZKLMax_{ur}$	Upper limit for the use of flextime of resource group $r(r \in R)$ in plant $u(u \in U)$ within a cycle (a multiple of a period $t(t \in T)$)
$initAnzR_{ur}$	Initial number of human resources in resource group $r(r \in R)$ in plant $u(u \in U)$
$initS_{us}$	Initial state of segment $s(s \in S_u)$ in plant $u(u \in U)$
$initShift_{us}$	Initial number of shifts on segment $s(s \in S_u)$ in plant $u(u \in U)$
$initU_u$	Initial state of plant $u(u \in U)$
$maxA_{uu'p}^{u}$	Maximum transport quantity of product $p(p \in C)$ from plant $u(u \in U)$ to plant $u'(u' \in U : u' \neq u)$
$minA_{ep}^{e}$	Minimum purchase quantity of product $p(p \in C)$ from external unit $e(e \in E_p)$
$minA_{lp}^{l}$	Minimum purchase quantity of the product $p(p \in C)$ from the supplier $l(l \in L_p)$
$minA_{uu'p}^{u}$	Minimum transport quantity of product $p(p \in C)$ from plant $u(u \in U)$ to plant $u'(u' \in U : u' \neq u)$
$minX_{up}$	Minimum production quantity for a product $p(p \in C)$ in plant $u(u \in U)$
$openU_u$	Fixed time $t(t \in T)$ at which plant $u(u \in U)$ is to be opened
$rAdaption_{ur}^{+/-}$	Upper limit for hiring $^{(+)}$ and laying off $^{(-)}$ natural resources $r(r \in R)$ in plant $u(u \in U)$
$reconfigU_u$	Reconfiguration frequency for plant $u(u \in U)$
$reconfigS_{us}$	Reconfiguration frequency for segment $s(s \in S_u)$ in plant $u(u \in U)$
$shiftMax_{us}$	Maximum number of shifts at segment $s(s \in S_u)$ in plant $u(u \in U)$
$stratU_u \in \{0,1\}$	Specifies whether a plant $u(u \in U)$ should remain open during the entire planning period

$$\sum_{1}^{per} FT_{u,r,zyk+per} \leq fTZKLMax_{ur} \cdot \frac{1}{per} \cdot \sum_{1}^{per} AnzR_{r,zyk+per} \quad (2)$$

with $t = zyk + per$

$\forall u \in U, r \in R, zyk \in ZKL$

$$\sum_{1}^{per} FT_{u,r,zyk+per} \geq 0 \quad (3)$$

with $t = zyk + per$

$\forall u \in U, r \in R, zyk \in ZKL$

With the introduction of flextime into the model, Eq. 4 for limiting the operating time must be extended.

$$\sum_{s \in S_{up}} \sum_{p \in C} ActR_{usrpt} \leq rHours_{ur} \cdot AnzR_{urt} + FT_{urt} \quad (4)$$

$\forall u \in U, r \in R, t \in T$

External capacities In addition to internal capacities, external units can also be used to balance demand peaks or bottleneck situations [37].

$$\sum_{u \in U} A_{eupt} \leq capE^{e}_{ep} \quad \forall p \in M, e \in E_p, t \in T \quad (5)$$

In particular, external units are intended to compensate for bottlenecks in the assembly of components that are later assembled to a final product. It is assumed that when a component is manufactured, the external entity makes all purchases of inputs itself and does not purchase any inputs from the focal company. The equation regarding the supply of production with intermediate products is extended by the term $\sum_{e \in E_p} A_{eupt}$ (see Appendix 6.1.1, Eq. 41).

$$\sum_{s \in S_{up}} \sum_{r \in R_{usp}} X_{usrpt} + \sum_{u' \in U_p} A_{u'upt} + \sum_{e \in E_p} A_{eupt} \geq \sum_{u' \in U} A_{uu'pt} + \sum_{d \in D_p} A_{udpt} + \sum_{s \in S_{up'}} \sum_{r \in R_{usp'}} \sum_{p' > p \in C} n_{pp'} \cdot X_{usrp't} \quad (6)$$

$\forall u \in U_p, p \in C, t \in T$

3.2.2 Reconfigurability aspects

If flexibility measures as in Sect. 3.2.1 are not sufficient to economically produce forecasted demand quantities, it is necessary to shift the flexibility corridor. This is done by reconfiguration of network objects and elements. Structural changes and measures to change capacity are accompanied by high investment costs [30]. In the following, the basic model is extended by the possibility of adapting network objects and human resources.

For reconfiguration decisions, a certain implementation time must be considered [38]. Therefore, no adaptations of this type can be made in period $t = 1$ in the model. These are only possible from period $t \geq 2$.

Adjustment of personnel resources

$$AnzR_{urt} - AnzRAdp^{+}_{urt} + AnzRAdp^{-}_{urt} - AnzR_{urt-1} = 0 \quad (7)$$

$\forall u \in U, r \in R_u, t \in T : t \geq 2$

The adaptation of personnel resources is not always possible without restrictions due to labor laws or the labor market. Therefore, limits for hiring and laying off of human resources are defined for each plant.

$$AnzRAdp^{+}_{urt} \leq rAdaption^{+}_{ur}$$
$$AnzRAdp^{-}_{urt} \leq rAdaption^{-}_{ur} \quad (8)$$

$\forall u \in U, r \in R_u, t \in T : t \geq 2$

Equation 9 ensures that only necessary personnel resources exist in a plant in any given period. However, it should be noted that this restriction may lead to more frequent personnel adaptations. In very unlikely cases this restriction in combination with $rAdaption^{+/-}_{ur} = 0$ and $AnzR_{urt=1} > 0$ can lead to an unsolvable planning problem.

$$AnzR_{urt} \leq \sum_{s \in S_{up}} \sum_{p \in C} ActR_{usrpt} \quad (9)$$

$\forall u \in U, r \in R_u, t \in T : t \geq 2$

Adjustment of the operating mode of segments A further adaptation measure is the change of the operating mode of individual segments. Fleischmann et al. [17] and Hochdoerffer [36] describe the adjustment of the operating mode as a restriction of the available capacity at a segment. The present work follows this definition. Thus, a shift model is integrated into the capacity constraint of segments.

$$\sum_{r \in R_{usp}} \sum_{p \in C} capP_{usrp} \cdot X_{usrpt} \leq effS_{us} \cdot capS_{us} \cdot \frac{AnzShift_{ust}}{shiftMax_{us}} \quad (10)$$

mit $AnzShift_{ust} \leq shiftMax_{us}$

$\forall u \in U, s \in S, t \in T$

Opening and closing of segments The following constraints enable the dynamic opening and closing of segments.

$$SAct_{ust} = SAct_{ust-1} + SAdp^{+}_{ust} - SAdp^{-}_{ust}$$
$$\text{with } SAdp^{+}_{ust} + SAdp^{-}_{ust} \leq 1 \quad (11)$$
$$\forall u \in U, s \in S_u t \in T : t \geq 2$$

Opening and closing of plants Analogous to the opening and closing of segments, the change of operating mode of whole plants is possible and ensured by the following constraint.

$$UAct_{ut} = UAct_{u,t-1} + UAdp^{+}_{ut} - UAdp^{-}_{ut}$$
$$UAdp^{-}_{ut} + UAdp^{+}_{ut} \leq 1 \quad (12)$$
$$\forall u \in U, t \in T : t \geq 2$$

$$\sum_{s \in S_u} SAct_{ust} \cdot sSpace_s \leq UAct_{ut} \cdot uSpace_u \quad (13)$$
$$\forall u \in U, t \in T$$

When opening or closing segments or plants, there are implications to consider, i.e., transport connections must not lead from or to plants that are closed and segments that are not open cannot be used. Thus, their usable capacity is zero.

$$UAct_{ut} = 0 \longrightarrow A_{lupt} = 0 \quad \forall l \in L, u \in U_p, p \in M, t \in T \quad (14)$$

$$UAct_{ut} = 0 \longrightarrow A_{eupt} = 0 \quad \forall e \in e, u \in U_p, p \in C, t \in T \quad (15)$$

$$UAct_{ut} = 0 \longrightarrow A_{u'upt} = 0 \quad \forall u \in U, u' \neq u \in U, p \in C, t \in T \quad (16)$$

$$UAct_{ut} = 0 \longrightarrow A_{uu'pt} = 0 \quad \forall u \in U, u' \neq u \in U, p \in C, t \in T \quad (17)$$

$$UAct_{ut} = 0 \longrightarrow A_{udpt} = 0 \quad \forall u \in U, d \in D, p \in C, t \in T \quad (18)$$

$$UAct_{ut} = 0 \longrightarrow X_{usrpt} = 0 \quad \forall u \in U, s \in S, r \in R, p \in C, t \in T \quad (19)$$

$$SAct_{ust} = 0 \longrightarrow X_{usrpt} = 0 \quad \forall u \in U, s \in S, r \in R, p \in C, t \in T \quad (20)$$

3.2.3 Other adaptation aspects

This section discusses other aspects of adaptation. These include minimum capacity utilization decision, strategic decisions made in advance, and brownfield planning.

3.2.3.1 Minimum production volume Especially in developing countries, local-content requirements are widespread [39]. In order to model them, a minimum production quantity $minX_{up}$ can be set for plant-product combinations in intra-company production.

$$\sum_{s \in S_u} \sum_{r \in R_{usp}} X_{usrpt} \geq minX_{up} \cdot UAct_{ut} \quad (21)$$
$$\forall u \in U, p \in C, t \in T$$

Minimum purchase quantities from suppliers and external units can be implemented in the same way. The parameters $minA^{l}_{lup}$ and $minA^{e}_{eup}$ are added to the model for this purpose.

$$\sum_{u \in U} A_{eupt} \geq minA^{e}_{ep} \quad (22)$$
$$\forall e \in E, p \in C, t \in T$$

$$\sum_{u \in U} A_{lupt} \geq minA^{l}_{lp} \quad (23)$$
$$\forall l \in L, p \in M, t \in T$$

Minimum $minA^{u}_{uu'p}$ and maximum $maxA^{u}_{uu'p}$ quantities can also be specified for transportation links between production sites.

$$A_{uu'pt} \geq minA^{u}_{uu'p} \quad \forall u \in U, u' \in U : u' \neq u, p \in C, t \in T \quad (24)$$

$$A_{uu'pt} \leq maxA^{u}_{uu'p} \quad \forall u \in U, u' \in U : u' \neq u, p \in C, t \in T \quad (25)$$

Strategic decisions in advance Sometimes it is necessary to consider strategic decisions made in advance in the model. For example, it may be the case that a new plant is already under construction and will be available in one of the later periods. The reverse case that a plant is to be closed is also conceivable. With the parameters $openU_u$ and $closeU_u$ fixed opening and closing times can be defined for a plant u.

$$UAdp^{+}_{ut} = 1 \quad \forall u \in U, t \in T : t = openU_u \quad (26)$$

$$UAct_{ut} = 0 \quad \forall u \in U, t \in T : t < openU_u \quad (27)$$

$$UAdp^{-}_{ut} = 1 \quad \forall u \in U, t \in T : t = closeU_u \quad (28)$$

$$UAct_{ut} = 0 \quad \forall u \in U, t \in T : t \geq closeU_u \quad (29)$$

If plants are not to be closed over the entire planning period, this can be set using the parameter $stratU_u \in \{0, 1\}$.

$$UAct_{ut} \geq stratU_u \qquad \forall u \in U, t \in T \tag{30}$$

In optimization models, it can happen that the status of plants and segments changes unrealistically often [27]. The parameters $reconfigU_u$ and $reconfigS_{us}$ can be used to minimize the reconfiguration frequency for segments and plants. If a reconfiguration frequency of 1 is selected, this means that a closed plant or segment may be opened, but not closed again during the planning horizon. A reconfiguration frequency of 0 eliminates that option completely.

$$\sum_{t \in T} \left(SAdp^{+}_{ust} + SAdp^{-}_{ust} \right) \leq reconfigS_{us} \quad \forall u \in U, s \in U_s \tag{31}$$

$$\sum_{t \in T} \left(UAdp^{+}_{ut} + UAdp^{-}_{ut} \right) \leq reconfigU_u \quad \forall u \in U \tag{32}$$

Brownfield planning One of the application areas of the optimization model is brownfield planning. This requires that initial states for certain decision variables can be specified in the form of parameters. In this model plants, segments, personnel resources and number of shifts of a segment can be defined. The first planning period $t = 1$ is assumed to be fixed, hence, the starting period for which the values are predefined.

$$UAct_{u,1} = initU_u \quad \forall u \in U \tag{33}$$

$$SAct_{u,s,1} = initS_{us} \quad \forall u \in U, s \in S \tag{34}$$

$$AnzR_{u,r,1} = initAnzR_{ur} \quad \forall u \in U, r \in R \tag{35}$$

$$AnzShift_{u,s,1} = initShift_{us} \quad \forall u \in U, s \in S \tag{36}$$

3.3 Multicriteria evaluation model

In practice, GPNs are not evaluated only on the basis of one objective [13, 40]. Often, the performance of a production network is evaluated and analyzed based on several criteria, such as cost or customer proximity [2]. Therefore, a multicriteria evaluation model consisting of two objective functions is developed:

- Minimization of total costs
- Maximization of customer proximity

Minimize total costs is chosen to represent a quantifiable objective in the multicriteria evaluation model. In addition to that it is a very common objective, as seen in the analysed models in chapter 2. Maximizing the customer proximity is a competing objective towards the total costs and it is very difficult to evaluate in monetary terms. This makes it a very interesting objective to evaluate and analyse in this chapter.

3.3.1 Minimization of total costs

Minimizing the costs incurred over the planning horizon is one of the most common objective criteria for planning models of GPNs. All optimization models considered in the literature review include costs in the evaluation model.

The total costs include both costs of operations and investment-related costs in order to support economic decisions [17]. In the proposed model, operational costs include variable and fixed costs in the basic model as well as cost components resulting from flexibility aspects. Reconfiguration costs are understood as investment-related costs.

Labor costs, costs for investments and exchange rates do not remain constant over a longer period of time [31]. In order to include price developments in the planning horizon, the cost parameters are period-specific.

All cost items and their respective equations can be found in appendix 1.

Objective function total costs The sum of all cost items provides the total costs incurred in the GPN over the planning horizon. The total costs are minimized in the evaluation model.

$$Min \quad \text{Total cost} \tag{37}$$

$$\begin{aligned}
= & \; Material\ costs \\
& + Processing\ costs \\
& + Transportation\ costs \\
& + Inventory\ costs \\
& + Costs\ for\ human\ resources \\
& + Fixedcosts\ plants \\
& + Fixedcosts\ segments \\
& + Costs\ for\ flextime \\
& + Costs\ for\ external\ units \\
& + Costs\ for\ the\ adj.\ of\ human\ resources \\
& + Costs\ for\ the\ adj.\ of\ plants \\
& + Costs\ for\ the\ adj.\ of\ segments
\end{aligned} \tag{38}$$

3.3.2 Maximizing customer proximity

In literature, examples of minimizing delivery time in GPNs can be found, e.g., [13, 31, 40]. In contrast, evaluating customer proximity in the planning model is uncommon in the literature. It is assumed that the focal company receives many engineer-to-order orders in a B2B context. For a successful cooperation with the customer and the fulfillment of an order, it is essential that local conditions, legal regulations and technical differences are known and understood [5]. Depending on the country and customer region, there can be major differences.

In the proposed model, customer proximity between production location and customer region is measured on the one hand by how much know-how specifically for a customer region is available at a location and on the other hand which production location is preferred by the customer for the fulfillment of an order.

The criterion of customer proximity cannot be evaluated objectively. Every company and every user will classify the location-customer relationship differently. In the proposed model, the user can decide this individually. The user chooses his own scale (e.g., 1–10) and evaluates the location-customer region relationship within this scale. However, the higher the number on the defined scale, the better the relationship. The parameter $closenessCust_{ud}$ stores the rating. For maximizing the customer proximity, the valuation factor $closenessCust_{ud}$ is now multiplied by the number of units of the product p delivered to the customer region d. The calculated sum value itself is not very meaningful, but during the optimization process, those locations u with which there is a better relationship are now preferred for the supply of customer regions d. If it is not desired that production sites send finished products from one site to another in order to achieve a better evaluation of customer proximity, the maximum transport quantities for finished products from site u to site u' $maxA^{u}_{uu'p}$ should be set to zero.

$$Max \quad \text{Customer proximity} = \sum_{t \in T} \sum_{u \in U} \sum_{d \in D} \sum_{p \in C} closenessCust_{ud} \cdot A_{udpt} \tag{39}$$

3.3.3 Solving multi-criteria optimization problems

One way to solve multi-criteria optimization problems is to map all objective criteria to a jointly measurable quantity, e.g., money [41]. However, competing goals cannot always be mapped to a scale in a meaningful way. For example, it is problematic to evaluate customer proximity in monetary terms.

Table 6 Lexicographic problem

Prio	Target criteria	Type	A/P	Delta
1	*Total costs*	Min	P	*deltaG*
2	*Customer proximity*	Max	P	*deltaK*

type: minimization or maximization, A/P: absolute or percentage deviation, delta: allowed deviation between optimal solution and solution under further requirements

In the context of multi-criteria evaluation, a useful concept is to consider Pareto-optimal solutions [41]. A solution x^* is called Pareto-optimal if there is no other admissible solution that is at least as good as the solution x^* with respect to all objective criteria and is not better in at least one objective criterion [42].

One approach to finding solutions of multi-criteria optimization problems is so-called Goal Programming [43]. The constructed evaluation model strives to minimize the deviation of the target criteria from their target marks. In this approach, the lexicographic variant of Goal Programming is used to transform the multi-objective optimization problem into ordinary linear programs and determine a Pareto-optimal solution [41, 44]. It is particularly suitable for models with incompatible goal criteria that can be put into a hierarchy but cannot be measured on a uniform scale.

A possible lexicographic problem for the proposed model with focusing on a cost-optimal design of the GPN while taking customer proximity into account could be stated as presented in Table 6.

The solution path of lexicographic goal programming is comprehensible and transparent for the user. It should be noted, however, that the chosen order of the goal criteria significantly influences the solution. Also, the allowed deviations (deltas), which denote the allowed difference between the optimal solution and the solution under further requirements (e.g., previous optimization runs) should be chosen carefully [44].

4 Real life application and discussion

The model was applied to a real-life case of a special machine manufacturer. The company produces high precision metrology machines. High customization possibilities throughout the entire product portfolio increase the production complexity. The GPN includes four production locations in the three main customer regions: two in Europe, and one each in Asia and North America. Based on the production of the last two years, the frequency of all components used is provided. This enables a systematic aggregation that results in 16 product groups, which represents the entire product portfolio. The customer demand is clustered into the four regions: Europe, Asia, North America and the rest of world. Raw material, resources, initial setup, transportation and custom costs are defined before applying the proposed model.

4.1 Validation

The suitability of the optimization model used for application as decision support tool is evaluated by three verification and validation techniques. First, a validation of

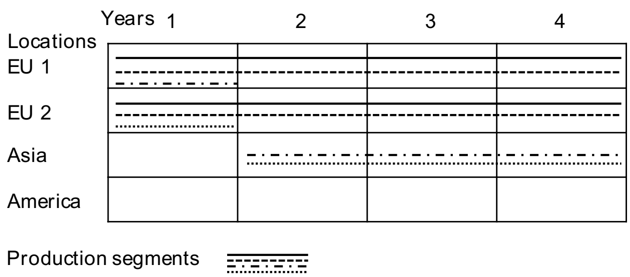

Fig. 1 Production network configuration

individual product variants takes place. This ensures the correct transfer of the bill of materials and assigned labor groups. Furthermore, it is reviewed if all required raw materials get purchased for the correct price and if the transportation costs are calculated correctly. This step is performed individually for each product before all products are considered in combination. In a second step, a case study is considered. Particular attention is given to the network configuration, the product allocation, the required resources and the resulting overall costs. Finally, the behavior of the optimization model is checked in extreme situations to ensure its feasibility for extreme cases of input parameters. For this purpose, three different limit value situations are reviewed.

4.2 Results of the multi-objective optimization model

In the optimization phase, all 16 product groups are considered with possibilities to produce at up to four production locations. The results of the optimization model are visualized in Fig. 1 and show that re-allocation of production capacities into low-cost countries in Asia takes place. Two production segments need to be opened in Asia in period 2 and the demand for the Asian market will be produced there. The equivalent segments in Europe will not be closed, but the capacity will be reduced meeting the new demand. The possible re-allocation of production capacities to America does not take place, as no cost saving is possible. The total cost saving between the status quo and the optimal cost solution is about 1%. As shown in Fig. 2, one reason for the small relative cost savings is the high share of raw material costs of the overall production network costs. As in this case only manual production steps are considered, the relocation is easy and the related one-time costs are negligible. Due to a confidentiality agreement, the complete and quantitative results cannot be disclosed in this section for illustrative purposes.

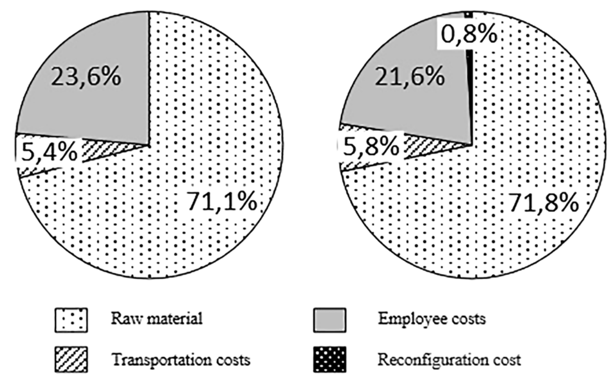

Fig. 2 Comparison of cost allocation status quo (left) and the optimal total cost solution (right)

4.3 Results of the post-optimality analysis

The goal of the post-optimality analysis is to investigate the identified solution for variations of assumptions made. This should give the decision makers better insights in the obtained solution and enhance the confidence in the results. Therefore, estimated or uncertain assumptions, i.e. resource costs, transportation costs or customs, are considered. Additionally, a shadow price analysis was conducted. In this analysis, further optimization potential is revealed with the expansion of resource capacities. Another method is also the slack variable analysis. A positive analysis shows that a resource group is not fully utilized and the overcapacity can be used or reduced otherwise. An illustration of the results for the variation of labor costs in Asia on the overall solution of the optimization model is shown in Fig. 3. With increasing labor costs, the total quantity of products assembled in Asia is decreasing. However, a small change of the labor costs has no effect on the production quantity. So, an increase of labor costs from 37 to 70 €/h leads to a decrease in the production volume by 257 units from 663 to 406 units, respectively ca. 39%.

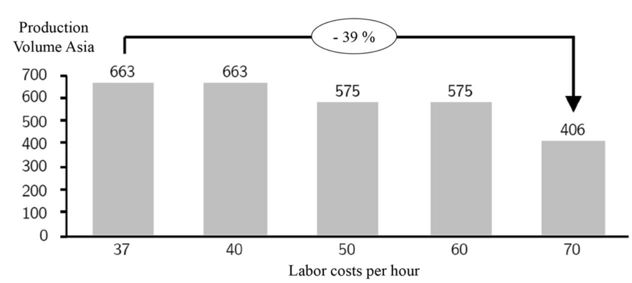

Fig. 3 Effect of variation of labor costs in Asia on production volume

5 Conclusion and outlook

The presented multi-objective optimization model facilitates the configuration of GPNs under consideration of flexibility and reconfigurability measures over long-term, strategic planning horizons. Due to its ability to consider multiple products and product variants, multi-criteria evaluation and multi-level production processes as well as external resources and capacities, the model fulfills requirements from real-world GPNs. Due to its general mathematical description and various possibilities of individualizing the model, it is possible to apply the model in various industrial contexts.

The implementation and validation of the model using real-life data of a special machine manufacturer shows the model's use and beneficiability. The aggregation of the product portfolio enables a faster data processing and solution finding. By additionally applying methods of post-optimality analysis, the identified solution can be investigated further and transparency for decision-makers in industry is given.

The developed optimization model can also be used easily across different industries because of the preconceived adaptation possibilities and potential within the boundaries of make-to-order or engineer-to-order production strategies. However, one should note that the results of the optimization model and post-optimality analysis highly depend on the availability and quality of input data. Thus, data acquisition, verification and preparation should be considered carefully. This is very time-consuming for a successful application, but can be implemented very well with the appropriate training. For an easier implementation, a practical guide would be highly recommended.

The optimization model can serve as a basis for diverse future research perspectives. Extending the existing solution regarding the consideration of the operative production program and scheduling of individual customer orders could be one option for future work. Moreover, taking into account the strategic perspective, i.e., aligning production strategy and the network footprint in order to quantify and optimize the network's resilience and adaptability, could be incorporated into the optimization model. A future scope could also be to expand the sensitivity analysis, in which the selection of the input parameters is varied and the size of the variation steps can be determined automatically.

Appendix

Base model

The base model includes the necessary material flow restrictions and capacity constraints of the GPN. Thus, it completely represents the network structure. Aspects of flexibility or reconfigurability are introduced later.

Table 7 Required sets in the base model

Set	Description
BOM	Bill of materials
$M \subset BOM$	Raw materials
$C \subset BOM$	C Describes a manufactured product. This can be a component of a final product
$F \subset C$	final product
S	Production segment
$S_u \subset S$	Potential segment in plant $u(u \in U)$
$S_p \subset S$	Segment which is able to produce product $p(p \in C)$
$S_{up} \subset S$	Segment which is able to produce product $p(p \in C)$ in plant $u(u \in U)$
R	Worker types
$R_u \subset R$	Potential worker type in plant $u(u \in U)$
$R_{sp} \subset R$	Worker type which is able to manufacture product $p(p \in C)$ on segment $s\left(s \in S_p\right)$
$R_{usp} \subset R$	Worker type which is able to manufacture product $p(p \in C)$ on segment $s\left(s \in S_p\right)$ in plant $u\left(u \in U_p\right)$
$PosCom$	Potential plant-segment-worker-product combination
$(u, s, r, p) \in PosCom$	Tuple of potential plant-segment-worker-product combinations
N	Nodes in the global production network
$L \subset N$	Potential suppliers
$L_p \subset L$	Suppliers who can deliver raw material $p(p \in M)$
$U \subset N$	Potential plants
$U_t^{+/-} \subset U$	Plants which are open $^{(+)}$ or closed $^{(-)}$ in period $t(t \in T)$
$U_p \subset U$	Plants where product $p(p \in M)$ is able to be produced
$D \subset N$	Customer region
$D_p \subset N$	Customer region for product $p(p \in F)$
T	Periods in the planning horizon

Table 8 Indices for the different sets

Index	Description
$d \in D$	Customer region
$l \in L$	supplier
$p, p' \in P$	Product
$r \in R$	Worker type
$s \in S$	Production segment
$u \in U$	Plant
$t \in T$	Period

All used indices, quantities, decision variables, and functional parameters are listed and described in the corresponding Tables 7, 8, 9 and 10.

Material flow equations and transport quantities

Fulfillment of customer demand It is assumed that customer demand must be met in each period.

$$\sum_{u \in U_p} A_{udpt} = dem_{pdt} \qquad \forall p \in F, d \in D, t \in T \tag{40}$$

Supply of production with intermediate products The quantity of produced and incoming products must be greater than or equal to the quantity of outgoing products for each plant.

$$\begin{aligned} &\sum_{s \in S_{up}} \sum_{r \in R_{usp}} X_{usrpt} + \sum_{u' \in U_p} A_{u'upt} \\ &\geq \sum_{u' \in U} A_{uu'pt} + \sum_{d \in D_p} A_{udpt} \\ &\quad + \sum_{s \in S_{up'}} \sum_{r \in R_{usp'}} \sum_{p' > p \in C} n_{pp'} \cdot X_{usrp't} \\ &\quad \forall u \in U_p, p \in C, t \in T \end{aligned} \tag{41}$$

Raw material demand The demand of the raw material results from the bill of materials. The factor $n_{pp'}$ indicates how many units of the product $p \in M \cup C$ are needed to produce one unit of the product $p' \in C$. The equation ensures that the raw material requirements are fulfilled.

$$\begin{aligned} &\sum_{l \in L_p} A_{lupt} \geq \sum_{s \in S_{up'}} \sum_{r \in R_{usp'}} \sum_{p' \in C} n_{pp'} \cdot X_{usrp't} \\ &\quad \forall p \in M, u \in U, t \in T \end{aligned} \tag{42}$$

Capacity restrictions

Segment capacities As mentioned above, manual assembly processes are assumed. Furthermore, there must always be an appropriately equipped segment, as well as a resource with the necessary know-how. The possible plant-segment-resource combinations to assemble a product are represented

Table 9 Decision variables in the base model

Decision variable	Description
A_{lupt}	Number of units of product $p(p \in M)$ transported from supplier $l(l \in L_p)$ to plant $u(u \in U)$ in period $t(t \in T)$
$A_{uu'pt}$	Number of units of product $p(p \in C)$ transported from pant $u(u \in U_p)$ to plant $u'(u' \in U; u' \neq u)$ in period $t(t \in T)$
A_{udpt}	Number of units of product $p(p \in F)$ transported from pant$u(u \in U_p)$ to customer region $d(d \in D_p)$ in period $t(t \in T)$
X_{usrpt}	Number of units of product $p(p \in C)$ produced in plant $u(u \in U)$ on segment $s(s \in S_{up})$ from worker type $r(r \in R_{usp})$ in period $t(t \in T)$
$AnzR_{urt}$	Number of workers of type $r(r \in R_{usp})$ in plant $u(u \in U)$ in period $t(t \in T)$
$ActR_{usrpt}$	Operating time of worker type $r(r \in R_{usp})$ in plant $u(u \in U_p)$ on segment $s(s \in S_{up})$ in period $t(t \in T)$

Table 10 Required functional parameters in the base model

Functional parameter	Description
$capL^l_{pl}$	Theoretical capacity limit for supplier $l(l \in L_p)$ for raw material $p(p \in M)$
$n_{pp'}$	Number of units of product $p(p \in M \cup C)$ required to make one unit of product $p'(p' \in X)$
$capS_{us}$	Theoretical capacity limit of segment $s(s \in S)$ in plant $u(u \in U)$
$effS_{us}$	Efficiency factor which reduces the theoretical capacity of segment $s(s \in S)$ in plant $u(u \in U)$
$capP_{usrp}$	Capacity requirement to manufacture product $p(p \in C)$ on segment $s(s \in S_{up})$ by worker type $r(r \in R_{usp})$ in plant $u(u \in U)$
dem_{pdt}	Demand of product $p(p \in F)$ in customer region $d(d \in D_p)$ in period $t(t \in T)$
$rHours_{ur}$	Regular working time of worker type $r(r \in R)$ in period $t(t \in T)$
$rGes_{urt}$	Upper bound on the number of workers of type $r(r \in R_u)$ in plant $u(u \in U)$ in period $t(t \in T)$
$sSpace_{us}$	Space required by segment $s(s \in S)$
$uSpace_u$	Total space available for segments at site $u(u \in U)$

in tuples of the form $(u, s, r, p) \in PosCom$. Here, the processing time of a product by a resource corresponds to the time during which the segment cannot be used for the assembly of another product. In the case where an assembly segment provides more than one workstation, it is assumed that assembly operations can take place in parallel and the capacity increases accordingly.

$$\sum_{r \in R_{usp}} \sum_{p \in C} capP_{usrp} \cdot X_{usrpt} \leq effS_{us} \cdot capS_{us} \quad \forall u \in U, s \in S, t \in T \tag{43}$$

Personnel resources In order to be able to use installed production segments, operating times of the resource groups $ActR_{usrpt}$ are assigned to each plant-segment-product combination. The tuple $(u, s, r, p) \in PosCom$ represents possible plant-segment-resource-product combinations (see decision variable X_{usrpt}). Theoretically, resource groups can be deployed at any plant-segment-product combination. In practice, however, e.g., contracts and know-how restrict the use of resource groups. For example, the exchange of resources between plants located in different countries is not possible at all or only possible to a limited extent. Likewise, the qualification plays a major role in the use of resources at different production segments.

$$\sum_{s \in S_{up}} \sum_{p \in C} ActR_{usrpt} \leq rHours_{ur} \cdot AnzR_{urt} \quad \forall u \in U, r \in R, t \in T \tag{44}$$

$$ActR_{usrpt} = capP_{usrp} \cdot X_{usrpt} \quad \forall u \in U, s \in S, r \in R, p \in C, t \in T \tag{45}$$

$$AnzR_{urt} \leq rGes_{urt} \qquad \forall u \in U, rinR, t \in T \tag{46}$$

Capacity restriction for suppliers

$$\sum_{u \in U} A_{lupt} \leq capL^{l}_{plt} \qquad \forall p \in M, l \in L_p, t \in T \tag{47}$$

Plant space

Table 11 Cost parameters of the basic model

Parameter	Description
$cost^{B}_{usrpt}$	Processing cost (e.g. auxiliary materials, tools) at "plant segment resource group product combination" $(u, s, r, p) \in PosCom$ in period $t(t \in T)$
$cost^{F}_{ut}$	Fixed costs for plant $u(u \in U)$ in period $t(t \in T)$
$cost^{F}_{ust}$	Fixed costs for segment $s(s \in S)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{M}_{lpt}$	Raw material cost for product $p(p \in M)$ from supplier $l(L \in L_p)$ in period $t(t \in T)$
$cost^{L}_{upt}$	Inventory cost rate of product $p(p \in C)$ from plant $u(u \in U)$ in period $t(t \in T)$
$cost^{R}_{urt}$	Costs for personnel resources $r(r \in r)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{T}_{lupt}$	Transportation cost of product $p(p \in M)$ from supplier $l(L \in L_p)$ to plant $u(u \in U)$ in period $t(t \in T)$
$cost^{T}_{uu'pt}$	Transportation cost of product $p(p \in C)$ from plant $u(u \in U)$ to plant $u'((u' \neq u) \in U)$ in period $t(t \in T)$
$cost^{T}_{udpt}$	Transportation cost of product $p(p \in C)$ from plant $u(u \in U)$ to customer region $d(d \in D_p)$ in period $t(t \in T)$
$leadTime_{usrp}$	Lead time at "plant segment resource group product combination" $(u, s, r, p) \in PosCom.$
$shippingTime^{U}_{uu'p}$	Transport time of product $p(p \in C)$ from plant $u(u \in U)$ to plant $u'((u' \neq u) \in U)$
$shippingTime^{D}_{udp}$	Transport time of product $p(p \in F)$ from plant $u(u \in U)$ to customer region $d(d \in D)$

Table 12 Cost parameters for the extensions of the basic model

Parameter	Description
$cost^{E}_{ept}$	Costs of delivering the product $p(p \in C)$ from the external entity $e(e \in E)$ in period $t(t \in T)$
$cost^{OT}_{u,r,zyk}$	Hourly rate for payment of flex time hours of personnel $r(r \in R)$ in plant $u(u \in U)$ at the end of a cycle $zyk(zyk \in ZKL)$
$cost^{R+}_{urt}$	Costs of hiring personnel $r(r \in r)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{R-}_{urt}$	Costs of laying off personnel $r(r \in r)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{S+}_{ust}$	Costs of opening segment $s(s \in S)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{S-}_{ust}$	Costs of closing the segment $s(s \in S)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{Shift}_{ust}$	Fixed costs per shift at segment $s(s \in S)$ in plant $u(u \in U)$ in period $t(t \in T)$
$cost^{U+}_{ut}$	Costs of opening the plant $u(u \in U)$ in period $t(t \in T)$
$cost^{U-}_{ut}$	Costs of closing the plant $u(u \in U)$ in period $t(t \in T)$

$$\sum_{s\in S_u} sSpace_s \leq uSpace_u \qquad \forall u \in U, t \in T \tag{48}$$

Total costs

Costs in the base model Cost parameters are introduced for each cost category. An overview of these is provided in Table 11 for the basic model and Table 12 for the extensions.

$$\text{Material costs} = \sum_{t\in T}\sum_{u\in U}\sum_{l\in L}\sum_{p\in M} cost^M_{lp} \cdot A_{lupt} \tag{49}$$

Processing costs

$$= \sum_{t\in T}\sum_{u\in U}\sum_{s\in S}\sum_{r\in R}\sum_{p\in C} cost^B_{usrpt} \cdot X_{usrpt} \tag{50}$$

Transportation costs

Transportation costs are highly dependent on contracts with customers and suppliers. It is assumed that suppliers deliver according to INCOTERM DDP: Delivered Duty Paid. For transportation costs, this means that the cost of transporting a product p from supplier l to plant u is not included in the transportation cost term (Eq. 51). Instead, any transportation/delivery costs incurred are then included in the purchase prices.

It is assumed that products are delivered to customers according to INCOTERM EXW: Ex Works (i.e., possession changes on the seller's premises [45]) or INCOTERM FCA: Free Carrier (i.e., possession changes when the seller has handed over the goods to the carrier [45]). Since this is not always feasible, the transportation costs from plant u to customer region d remain in the transportation cost term. Depending on the use case, they can be excluded.

Transport costs

$$\begin{aligned} &= \sum_{t\in T}\sum_{u\in U}\sum_{(u'\neq u)\in U}\sum_{p\in C} cost^T_{uu'pt} \cdot A_{uu'pt} \\ &+ \sum_{t\in T}\sum_{u\in U}\sum_{d\in D}\sum_{p\in C} cost^T_{udpt} \cdot A_{udpt} \end{aligned} \tag{51}$$

Inventory costs As mentioned above, a make-to-order or engineer-to-order principle is assumed. Significant warehouse centers in the network are therefore not necessary and inventory costs are avoided. However, costs are incurred for circulating inventories in the GPN. These are caused on the one hand by semi-finished products and on the other hand by goods on transports between the production sites or to the end customer. For inventory costs, the same assumptions for INCOTERMS apply as for the transportation costs.

Inventory costs

$$\begin{aligned} &= \sum_{t\in T}\sum_{u\in U}\sum_{p\in C} cost^L_{upt} \cdot \sum_{s\in S}\sum_{r\in R} leadTime_{usrp} \cdot X_{usrpt} \\ &+ \sum_{t\in T}\sum_{u\in U}\sum_{p\in C} cost^L_{upt} \\ &\quad \cdot \sum_{(u'\neq u)\in U} shippingTime^U_{uu'p} \cdot A_{uu'pt} \\ &\quad + \sum_{t\in T}\sum_{u\in U}\sum_{p\in F} cost^L_{upt} \\ &\quad \cdot \sum_{d\in D} shippingTime^D_{udp} \cdot A_{udpt} \end{aligned} \tag{52}$$

Personnel costs

Personnel costs

$$= \sum_{t\in T}\sum_{u\in U}\sum_{r\in R} cost^R_{urt} \cdot rHours_{ur} \cdot AnzR_{urt} \tag{53}$$

Fixed costs for plants and segments Fixed costs are incurred for plants and segments regardless of the volume. These include rental costs, maintenance costs, and the volume independent energy costs.

$$\text{Fixed costs for plants} = \sum_{t\in T}\sum_{u\in U} cost^F_{ut} \cdot UAct_{ut} \tag{54}$$

Fixed costs for segments

$$= \sum_{t\in T}\sum_{u\in U}\sum_{s\in S} cost^F_{ust} \cdot SAct_{ust} \tag{55}$$

Costs for flextime Equation 56 is used to determine the costs incurred for the payment of overtime at the end of the cycle. The cost of each overtime hour worked by personnel r is $cost^{OT}_{u,r,zyk}$. Restriction 3 excludes the possibility of negative flextime at the end of a cycle. Thus, the term $\sum_{per\in PER} FT_{u,r,zyk+per}$ always takes values greater zero.

$$\begin{aligned} \text{Costs for flextime} &= \sum_{zyk\in ZYK}\sum_{u\in U}\sum_{r\in R} cost^{OT}_{u,r,zyk} \\ &\cdot \sum_{per\in PER} FT_{u,r,zyk+per} \end{aligned} \tag{56}$$

Costs for external units External units are valued like suppliers. Inefficiencies of the external capacity are not remunerated.

Costs for external units

$$= \sum_{t\in T}\sum_{e\in E}\sum_{u\in U}\sum_{p\in C} cost^E_{ept} \cdot A_{eupt} \tag{57}$$

Costs for the adjustment of personnel resources

$$= \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} \sum_{r \in R} cost_{urt}^{R+} \cdot AnzRAdp_{urt}^{+} + \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} \sum_{r \in R} cost_{urt}^{R-} \cdot AnzRAdp_{urt}^{-} \quad (58)$$

Costs for the adjustment of plants

$$= \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} cost_{ut}^{U+} \cdot UAdp_{ut}^{+} + \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} cost_{ut}^{U-} \cdot UAdp_{ut}^{-} \quad (59)$$

Costs for the adjustment of segments

$$= \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} \sum_{s \in S} cost_{ust}^{S+} \cdot SAdp_{ust}^{+} + \sum_{\substack{t \in T: \\ t \geq 2}} \sum_{u \in U} \sum_{s \in S} cost_{ust}^{S-} \cdot SAdp_{ust}^{-} \quad (60)$$

The introduction of the shift model for segments also changes the fixed cost equation 55. The cost factor $cost_{ust}^{F}$ now summarizes all costs that are incurred regardless of the selected number of shifts $AnzShift_{ust}$. All costs that are attributable to a shift (e.g., attributable energy costs or indirect personnel) are recorded in the parameter $cost_{ust}^{Shift}$. The box marked in green contains the added formula part.

Fixed costs for segments with shift model

$$= \sum_{t \in T} \sum_{u \in U} \sum_{s \in S} cost_{ust}^{F} \cdot SAct_{ust} + \sum_{t \in T} \sum_{u \in U} \sum_{s \in S} cost_{ust}^{Shift} \cdot AnzShift_{ust} \quad (61)$$

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