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Abstract

An important concern in supply chain management is about network design, involving factories, central warehouses, regional warehouses as well as customers. The best strategy has to be ascertained for distributing products within this network. The objective is to select the optimal numbers and locations of central and regional warehouses such that all customer demands are satisfied at minimum total costs of the network. An extension of existing approaches is to take into account aspects of postponement, in particular regarding the problem of postponing activities like assembling half-finished goods or packaging them. A mixed integer programming model is provided and it is demonstrated that the resulting formulation can be used to solve realistic problem instances with commercially available mathematical programming software.

1 Introduction

Designing the physical distribution network in a supply chain is an important strategic planning problem with undeniable implications towards tactical and operational planning success. In this paper we consider a distribution network made up of four tiers (factories, central warehouses, regional warehouses, and customer zones (demand points)), with the aim of defining the number and location of different types of facilities. Moreover, we consider certain postponement options motivated by some real-world cases. Aspects of postponement are a widely recognized approach to improve supply chains. However, up to now they have not yet been fully integrated in advanced planning tools [SkHa04], [Stad05]. Various postponement definitions can be found in literature. To some authors, postponement simply means delaying at least one differentiating step. To others, postponement rather means adding variety after receiving a customer order than anticipating orders [ApGu05]. In the context of distribution network design postponing activities means that finishing products in factories is not mandatory. In lieu of this, performing activities like, e.g., assembling or packaging can be procrastinated. This requires the implementation of appropriate functions in central warehouses or regional warehouses for assembling or packaging goods, respectively.

In this paper a mixed integer linear programming (MILP) model for distribution network design is developed. This model permits decisions regarding the number and location of different types of potential facilities to be selected from a set of possible candidates. As an extension of existing models, decisions regarding the establishment of delayed functions to finish a product with respect to customer requirements are also taken into account. The objective in designing such a distribution network is to determine a least cost system design that satisfies the demands of all customers without exceeding the capacities of the factories, the warehouses including their implemented functions to finish a product as well as the capacities of the shipping routes between the facilities. The model belongs to the class of production-distribution allocation as well as facility-location allocation problems.

The remainder of the paper is organized as follows. In Section 2, a literature review on planning distribution networks as well as postponement is given. In Section 3, a specific distribution network incorporating postponement approaches is depicted in detail. Section 4 contains a mathematical formulation of the considered problem. In Section 5, some computational results for two test instances are reported indicating that respective models actually may prove useful in today's planning systems. A summary as well as an outlook to further research are given in Section 6.

2 Literature review

Designing a distribution network in a multi-echelon environment for locating distribution facilities and allocating functions for finishing products regarding customer needs requires strategic decisions (where to locate facilities and implement functions) as well as tactical/operational decisions (distribution strategy from factories to customers via central as well as regional warehouses). In Operations Research, models and methods for distribution planning are available since its early years, in particular for locating warehouses, but also for more comprehensive design problems regarding multiple products, limited capacities, single source constraints or nonlinear transportation costs (see, e.g., the reviews of [Aike85], [OwDa98] or [KlDr05]). [GeGr74] were among the first to investigate the use of intermediate distribution. They present a model to solve the problem of designing a distribution system with an optimal location of intermediate distribution facilities between factories and customers. [BrGH87] depict an optimization-based algorithm for a decision support system used to manage complex problems involving facility selection, equipment location and utilization, as well as manufacturing and distribution of products. A MILP formulation with the objective of maximizing the total after-tax profit for manufacturing facilities and distribution centers is presented by [CoLe89]. The model determines the optimal deployment of resources associated with a particular policy option. The considered product structure in the model encompasses three levels (major components, subassemblies, finished products). Extending the model of [CoLe89], [CoMo90] investigate effects of various parameters on supply chain costs and determine which manufacturing facilities and distribution centers should be established. [Chan93] uses a model that plans besides vehicle routes deliveries to customers based upon inventories at warehouses and distribution centers. Later, [ChFi94] consider the coordination of production and distribution planning. [Flei93] developed a multi-commodity three-stage network flow model with arbitrary nonlinear transport and warehouse costs which may include fixed costs. In contrast to common models, location decisions are not determined by integer programming or add/drop procedures, but result from the solution of a network flow problem. A MILP model presented by [Pool94] allows for deciding where to locate factories and depots, allocating the production as well as how to serve customers. A MILP global supply chain model presented by [ABHT95] determines the number and location of distribution centers, customer-distribution center assignments, the number of tiers, and the product-factory assignment. [CCDE97] developed an integer model for finding the location of distribution centers and to assign those selected to customer zones. [Amir06] presents a model that takes into consideration different capacity levels. A tri-echelon multi-commodity system incorporating production, transportation and distribution planning is considered by [PiJa96]. In a succeeding work, [JaPi01] present a model that determines the location of a number of production plants and distribution centers with the objective of minimizing the total operating costs for the distribution network. Further models of distribution networks with several layers are also presented in, e.g., [Klin85], [TsSP01] or [AmSc05]. A multi-objective approach is pointed out in [SaBe00]. A distribution network model taking into account mode selection, lead times as well as capacitated vehicle distribution centers is proposed in [EUPB05].

[KaMN03] develop a generic strategic planning and design model for global supply chains which captures essential elements of many industrial environments. Further papers concerning distribution networks can be found in comprehensive reviews of, e.g., [ViGo97], [GoVD02] and [BiOz04].

Postponement is widely regarded as an approach that may result in superior supply chains (e.g., [JoRi85] or [Coop93]), and it has been recognized as a growing trend in manufacturing and distribution [SkHa04]. According to [YaBu03], much has been written in the literature on the benefits of postponement, yet little is known about its implementation.

Extensive investigations of benefits of postponement as well as postponement strategies have been carried out in the context of marketing and logistics as well as supply chain management. Some papers in this context are [Alde50], [Buck65], [ZiBo88], [Coop93], [FeLe97], [PaCo98], [vHoe98], [vHoe01] and [YaBu03] as well as [MiSk04]. Whereas these studies are primarily qualitative, some recent papers focus on quantifying the benefits and criteria of various postponement strategies. See, e.g., [LeBC93], [GaTa97], [SwTa99], [ErKa00], [MaWL02], [YeYa03], [SkHa04] or [ApGu05].

None of the papers discussed above explicitly deals with the implementation of postponement strategies in the context of planning a distribution network, and there are only few papers, e.g., [CoLe89], [CoMo90] or [ABHT95] that rudimentary combine aspects of postponement and distribution network design.

3 Designing distribution networks allowing for aspects of postponement

This work considers a distribution network with several facilities at different tiers of the network where different products are delivered from the plants to satisfy the requirements of several customer zones. Figure 1 shows a distribution network with factories, central warehouses, regional warehouses and customer zones. The arrows represent potential flows of the products from the factories up to the customer zones. Typically, the goods flow from factories to central warehouses, from central warehouses to regional warehouses and then to the customer zones. The locations of central and regional warehouses are unknown and have to be selected from a set of candidate locations. Furthermore, there is also the alternative to ship goods directly from factories to regional warehouses, from central warehouses to customer zones as well as from factories up to customer zones.

In the distribution network, different groups of finished or unfinished products are shipped to one or several central warehouses in order to be shipped in common from there. Regional warehouses serve as destinations of shipments from the factories or central warehouses, and as starting points for short-distance deliveries to customers. They permit to bundle the shipped goods over long distances, before splitting them into smaller quantities regarding customer orders. The customer zones comprise several customers within an enclosed area. Each customer zone has some demand for certain products, which has to be met by the distribution system.

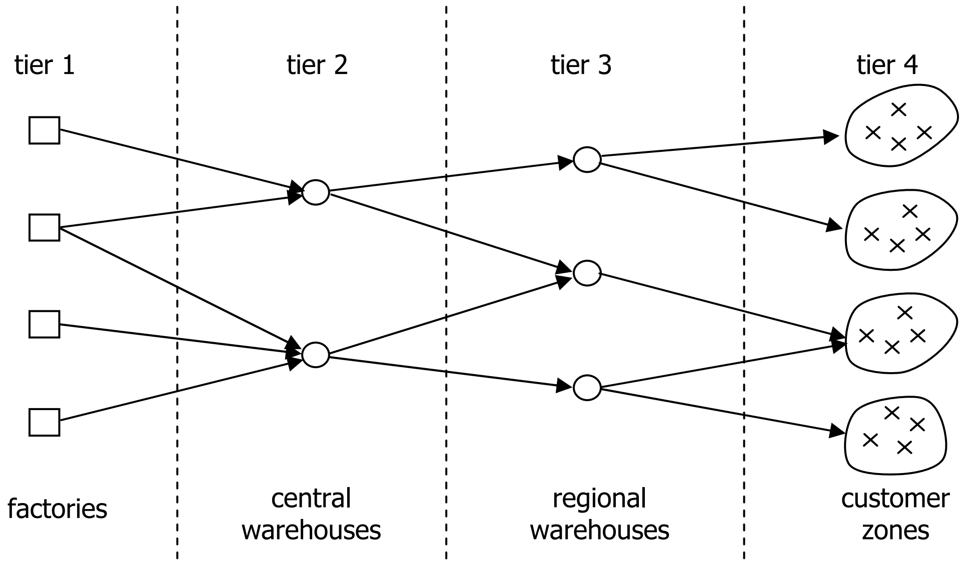

Figure 1: Distribution network with four tiers

Common models of distribution network planning assume that they comprise a flow of finished products from factories to customers. Here this assumption is relaxed such that activities to finish a product could be performed later, or rather postponed along the route from the factories up to the customers. Potential locations for postponed activities are both central and regional warehouses. [ZiBo88] describe five types of postponement that could be implemented in a distribution network: These types of postponement comprise labeling postponement, packaging postponement, assembly postponement, manufacturing postponement, and time postponement. Labeling postponement is an approach where standard products are stocked and labeled differently regarding the realized customer demand. In packaging postponement, products are not packaged into individual packs until final orders are received. Assembly and manufacturing postponement refer to situations where additional assembly or manufacturing may be performed in assembly facilities or at warehouses before shipping the products to customers after demand is realized. Finally, time postponement represents the concept that products are held at a central warehouse and are shipped to customers directly, instead of shipping them in advance in virtue of corresponding forecasts to retail warehouses.

In the considered distribution network planning problem two types of postponement strategies are to be established: Packaging postponement as well as assembly postponement (see, e.g., [Coop93]). The motivation behind these postponements stems from the option to utilize respective degrees of freedom. That is, products may eventually be specified according to either the final assembly step or even the packaging. Especially for regions with large varieties in customer demands for one or the other product this may allow additional degrees of freedom. Regarding the implementation of the corresponding processes to assemble unfinished goods respectively to pack finished goods, the required resources can be installed on every tier of the distribution network, namely in the factories, in the central warehouses, or in the regional warehouses. Feasible routings through the distribution network are depicted in Figure 2.

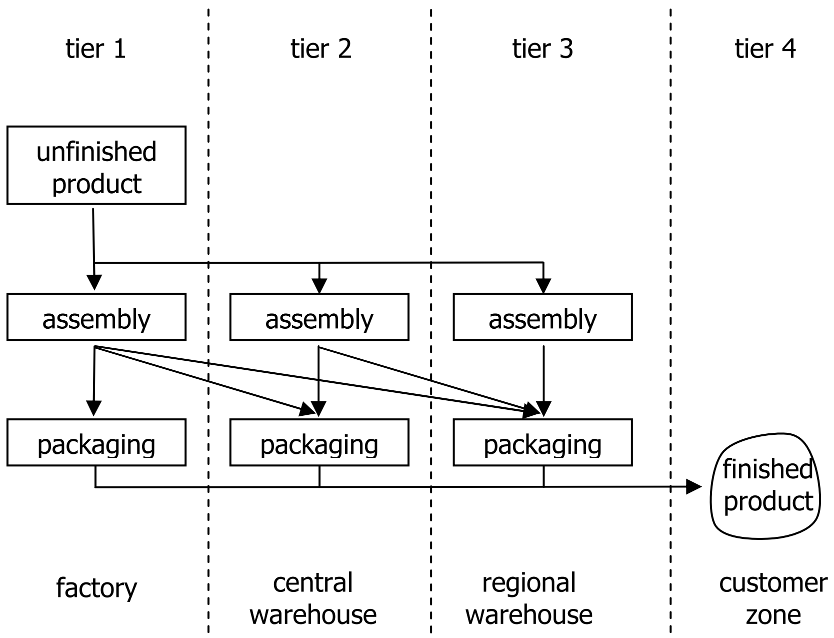

Figure 2: Feasible routings through the distribution network

Postponement may result in considerable cost tradeoffs. Regarding the considered assembly and packaging postponement strategies, processing costs for assembly respectively packaging increase and the transportation costs decrease. Increased per unit assembly costs as well as increased per unit packaging costs result from reduced economies of scale in the concerned warehouses in contrast to assembly respectively packaging in a central plant. Regarding unfinished products that have yet to be assembled, the reduction of transportation costs is typically due to a better density ratio of unassembled products compared to assembled products. In the context of packaging products, a reduction of transportation costs results from bulk shipping finished, but not packed products from factories to central respectively regional warehouses or from central warehouses to regional warehouses.

The decisions to be determined in the presented distribution network design problem represent strategic decisions and include decisions concerning the number and location of potential central and regional warehouses to be established as well as the decision where to implement assembly and packaging functions in the distribution network. As mentioned above, possible locations for assembly and packaging functions are factories, central warehouses and regional warehouses. Furthermore, decisions regarding the quantity of products shipped between facilities have to be made. The objective is to minimize the combined total costs of the network for a given demand of several customers, taking into account both fixed infrastructure and variable operating costs. The developed model represents a steady-state form of the considered problem with time-invariant deterministic demands. The quantities determined by the optimization are considered to be time-averaged quantities.

Figure 3 represents a consolidated view of Figures 1 and 2. To ease comprehension of the mathematical model in the next section, the applied indices for different locations of facilities or customer zones (i), functions (f and l) and tiers (s) are incorporated in Figure 3. Index l denotes different functions that could be implemented in a facility. Index f also distinguishes different functions that could be implemented. Furthermore, index f interprets identical functions that deal with products with different completion status as different functions. For reason of clarity there is only one facility displayed at each tier. Further potential facilities in alternative locations at a tier as well as the corresponding flows are omitted. The displayed flows in Figure 3 comprise flows between facilities (shipping goods from one location to another one) as well as flows within facilities (processing goods). On the one hand, the arrows between facilities represent feasible process-determined sequences of functions implemented at facilities that have to be applied to finish a product in the production-distribution process. On the other hand, they indicate the changeover from a facility at one location to a facility at another one at a subsequent tier. There are also some arrows included that represent bypassing one and two tiers respectively.

In every facility displayed in Figure 3, various functions that are allowed to be implemented are shown. These functions include the function “no action” that simply refers to handling products without performing any activities like, e.g., assembly or packaging. At the second tier, the activity “no action” is represented by three nodes. This is due to the requirement to distinguish products with different completion status in a facility. The ability to distinguish products with different completion status is needed again both to determine the allowed succeeding activity in the distribution network, and to calculate the correct capacity consumption in the corresponding facility.

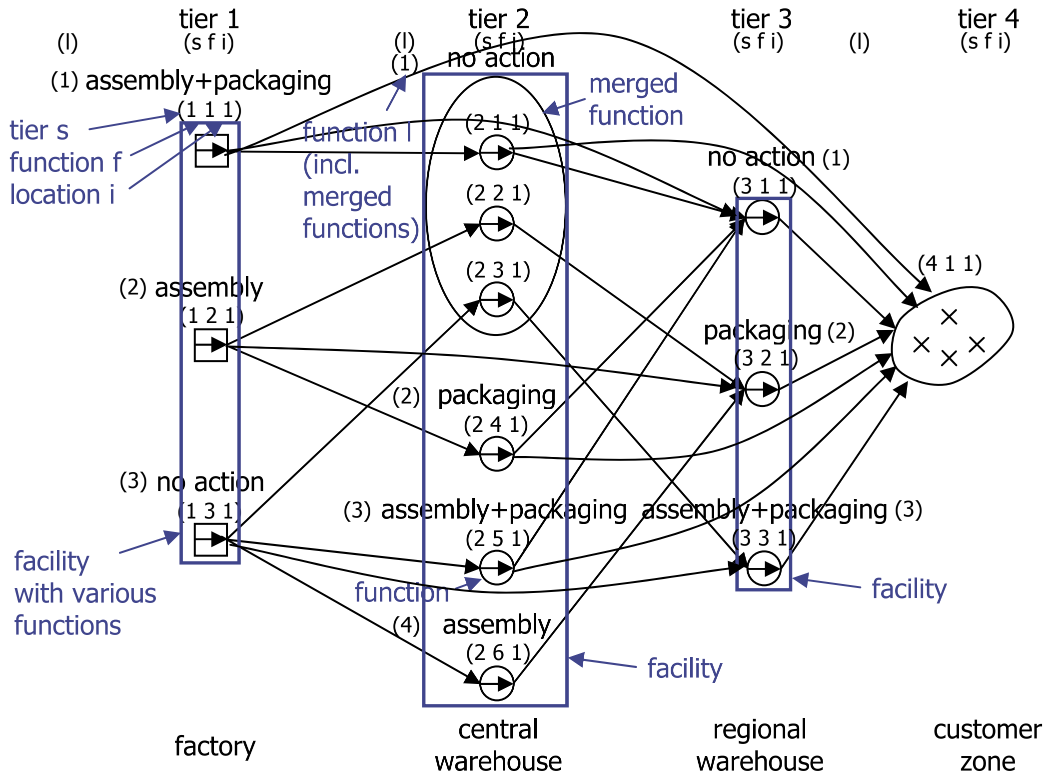

Figure 3: Distribution network with postponed activities

4 Model formulation

The integrated mathematical model for distribution network planning with postponement represents a cost minimization problem. It is a steady state model with deterministic demands, and it is represented by a mixed integer programming formulation. The following notation is used in the formulation of the model:

S	number of tiers
Z	index set of products
L_s	index set of different functions at tier s
FCT_s	index set of nodes of tier s that represents various functions for various degrees of a product’s completion

$LFCT_{sl}$ index set of nodes of tier s that represents the same function $l \in L_s$ for various degrees of a product's completion

LOC_s index set of potential locations of facilities at tier s

$LINKFCT1S_s$ / $LINKFCT2S_s$ / $LINKFCT3S_s$ allowed sequences of potential consecutive functions at tiers s and s+1 / s+2 / s+3

$LINKLOC1S_s$ / $LINKLOC2S_s$ / $LINKLOC3S_s$ allowed transportation links (facility/facility or facility/customer zone) at tiers s and s+1 / s+2 / s+3

The decision variables are:

x^{c1S}_{zsijfg} / x^{c2S}_{zsijfg} / x^{c3S}_{zsijfg} quantities of product z shipped from a facility at candidate location i at tier s to a facility at candidate location j at tier s+1, performing function f in facility i and function g in facility j

x^{i}_{zsif} quantity of product z processed in a facility at candidate position i at tier s by the implemented function f

y_{sil} 1, if function l is established in facility i at tier s; 0 otherwise

The decision variables x^{c2S}_{zsijfg} and x^{c3S}_{zsijfg} represent a bypassing of facilities of one and two tiers respectively.

Furthermore, the following parameters are taken into account:

c^{c}_{zsf} shipping cost per unit and per unit distance for a product z processed by function f at tier s

d^{1S}_{sij} / d^{2S}_{sij} / d^{3S}_{sij} distances between facility i at tier s and facility j at tier s+1 / s+2 / s+3

c^{i}_{zsif} processing cost for product z of an implemented function f in a facility at candidate location i at tier s

c^{f}_{sif} fixed cost of establishing an implemented function f in a facility at candidate location i at tier s

U^{i}_{zsif} maximum throughput quantity for product z (handling and inventory) at a facility in location i at tier s for the implemented function f

U^{c1S}_{zsijf} / U^{c2S}_{zsijf} / U^{c3S}_{zsijf} maximum shipping quantities for product z from a facility in location i at tier s to a facility in location j at tier s+1 / s+2 / s+3 after completing activity f implemented in i

Dem_{zi}	demand of product z in customer zone i
Sup_{zi}	supply of product z in factory i

In terms of the above notation, the problem can be stated as follows:

Problem P:

$$\min \sum_{\substack{z\in Z\\ s\in\{1,2,\dots,S-1\}\\ (i,j)\in LINKLOC1S_s\\ (f,g)\in LINKFCT1S_s}} c^{c1S}_{zsf} d^{c1S}_{sij} x^{c1S}_{zsijfg} + \sum_{\substack{z\in Z\\ s\in\{1,2,\dots,S-2\}\\ (i,j)\in LINKLOC2S_s\\ (f,g)\in LINKFCT2S_s}} c^{c2S}_{zsf} d^{2S}_{sij} x^{c2S}_{zsijfg} + \sum_{\substack{z\in Z\\ s\in\{1,2,\dots,S-3\}\\ (i,j)\in LINKLOC3S_s\\ (f,g)\in LINKFCT3S_s}} c^{c3S}_{zsf} d^{3S}_{sij} x^{c3S}_{zsijfg} + \sum_{\substack{z\in Z\\ s\in\{1,2,\dots,S-1\}\\ i\in LOC_s\\ f\in FCT_s}} c^{i}_{zsif} x^{i}_{zsif} + \sum_{\substack{s\in\{1,2,\dots,S-1\}\\ i\in LOC_s\\ l\in L_s}} c^{f}_{sil} y_{sil} \quad (1)$$

subject to:

Material balance constraints

Flows entering a facility

$$x^{i}_{zsjg} = \sum_{\substack{(i,j)\in LINKLOC1S_{s-1}\\ (f,g)\in LINKFCT1S_{s-1}}} x^{c1S}_{z(s-1)ijfg} \qquad \forall z\in Z, s=2, j\in LOC_s, g\in FCT_s \quad (2)$$

$$x^{i}_{zsjg} = \sum_{\substack{(i,j)\in LINKLOC1S_{s-1}\\ (f,g)\in LINKFCT1S_{s-1}}} x^{c1S}_{z(s-1)ijfg} + \sum_{\substack{(i,j)\in LINKLOC2S_{s-2}\\ (f,g)\in LINKFCT2S_{s-2}}} x^{c2S}_{z(s-2)ijfg} \qquad \forall z\in Z, s=3, j\in LOC_s, g\in FCT_s \quad (3)$$

Demand

$$Dem_{zj} = \sum_{\substack{(i,j)\in LINKLOC1S_{s-1}\\ (f,g)\in LINKFCT1S_{s-1}}} x^{c1S}_{z(s-1)ijfg} + \sum_{\substack{(i,j)\in LINKLOC2S_{s-2}\\ (f,g)\in LINKFCT2S_{s-2}}} x^{c2S}_{z(s-2)ijfg} + \sum_{\substack{(i,j)\in LINKLOC3S_{s-3}\\ (f,g)\in LINKFCT3S_{s-3}}} x^{c3S}_{z(s-3)ijfg} \quad \forall z\in Z, s=4, j\in LOC_s, g\in FCT_s \quad (4)$$

Flows leaving a facility

$$x^{i}_{zsif} = \sum_{\substack{(i,j)\in LINKLOC1S_s\\ (f,g)\in LINKFCT1S_s}} x^{c1S}_{zsijfg} + \sum_{\substack{(i,j)\in LINKLOC2S_s\\ (f,g)\in LINKFCT2S_s}} x^{c2S}_{zsijfg} + \sum_{\substack{(i,j)\in LINKLOC3S_s\\ (f,g)\in LINKFCT3S_s}} x^{c3S}_{zsijfg} \qquad \forall z\in Z, s=1, i\in LOC_s, f\in FCT_s \quad (5)$$

$$x^{i}_{zsif} = \sum_{\substack{(i,j)\in LINKLOC1S_s\\ (f,g)\in LINKFCT1S_s}} x^{c1S}_{zsijfg} + \sum_{\substack{(i,j)\in LINKLOC2S_s\\ (f,g)\in LINKFCT2S_s}} x^{c2S}_{zsijfg} \qquad \forall z\in Z, s=2, i\in LOC_s, f\in FCT_s \quad (6)$$

$$x^{i}_{zsif} = \sum_{\substack{(i,j)\in LINKLOC1S_s\\ (f,g)\in LINKFCT1S_s}} x^{c1S}_{zsijfg} \qquad \forall z\in Z, s=3, i\in LOC_s, f\in FCT_s \quad (7)$$

Supply

$$Sup_{zi} \ge \sum_{f\in FCT_s} x^{i}_{zsif} \qquad \forall z\in Z, s=1, i\in LOC_s \quad (8)$$

Capacity constraints

Transport capacity

$$\sum_{z \in Z} \frac{x_{zsijfg}^{c1S}}{U_{zsijf}^{c1S}} \leq 1 \qquad \forall s \in \{1,2,...,S-1\}, (i,j) \in LINKLOC1S_s, (f,g) \in LINKFCT1S_s \tag{9}$$

$$\sum_{z \in Z} \frac{x_{zsijfg}^{c2S}}{U_{zsijf}^{c2S}} \leq 1 \qquad \forall s \in \{1,2,...,S-2\}, (i,j) \in LINKLOC2S_s, (f,g) \in LINKFCT2S_s \tag{10}$$

$$\sum_{z \in Z} \frac{x_{zsijfg}^{c3S}}{U_{zsijf}^{c3S}} \leq 1 \qquad \forall s \in \{1,2,...,S-3\}, (i,j) \in LINKLOC3S_s, (f,g) \in LINKFCT3S_s \tag{11}$$

Facility capacity

$$\sum_{\substack{z \in Z \\ f \in LFCT_{sl}}} \frac{x_{zsif}^{i}}{U_{zsif}^{i}} \leq y_{sil} \qquad \forall s \in \{1,2,...,S-1\}, i \in FCT_s, l \in L_s \tag{12}$$

Non-negativity constraints

$$x_{zsijfg}^{c1S} \geq 0 \qquad \forall z \in Z, s \in \{1,2,...,S-1\}, (i,j) \in LINKLOC1S_s, (f,g) \in LINKFCT1S_s \tag{13}$$

$$x_{zsijfg}^{c2S} \geq 0 \qquad \forall z \in Z, s \in \{1,2,...,S-2\}, (i,j) \in LINKLOC2S_s, (f,g) \in LINKFCT2S_s \tag{14}$$

$$x_{zsijfg}^{c3S} \geq 0 \qquad \forall z \in Z, s \in \{1,2,...,S-3\}, (i,j) \in LINKLOC3S_s, (f,g) \in LINKFCT3S_s \tag{15}$$

$$x_{zsif}^{i} \geq 0 \qquad \forall z \in Z, s \in \{1,2,...,S-1\}, i \in LOC_s, f \in FCT_s \tag{16}$$

Binary constraints

$$y_{sil} \in \{0;1\} \qquad \forall s \in \{1,2,...,S-1\}, i \in LOC_s, l \in L_s \tag{17}$$

Objective function (1) consists of three cost types. At first, the objective function encompasses variable shipping costs between the locations of facilities. The costs are assumed to be linear. Nonlinear shipping costs, taken into account, e.g., in [Flei93] or [TsSP01], could be incorporated into a more comprehensive model presented in a subsequent paper. A further type of costs in the objective function is induced by variable processing costs at the locations of the facilities. Activities taken into account that could be implemented at the considered facilities are assembly, packaging, both assembly and packaging in combination, as well as a simple handling of products in a facility without executing any further activities. The third cost type represents infrastructure costs with a fixed cost character for establishing the considered functions in the facilities. Constraint sets (2) and (3) represent material balances. The flow entering a facility must equal the quantity that is processed in this facility. Analogously, constraint sets (5), (6) and (7) declare material balances which ensure that the flow leaving a facility has to be as high as the quantity that is processed there. Constraint set (4) assures that every customer's zone demand for each product type is met. Constraint set (8) restricts the material flows leaving the factories to their maximum quantity they are able to supply. With constraint sets (9) - (11), the maximum quantity of products that can be shipped from one location to another one is incorporated into the distribution network model. The total capacity consumption by shipping different products along the same link is calculated by a linear combination of the capacity consumption of individual products. Constraint set (12) represents a similar approach regarding the maximum quantity that can be processed by an implemented function within a facility. The binary variables in constraint set (12) indicate weather a specific function should be established in a facility or not. Furthermore, the constraints also permit calculating the capacity consumption in a facility if the products processed with the implemented function in the facility feature different completion status (see Figure 3 and its explanations in Section 3). Constraint sets (13) - (16) act for non-negativity constraints, constraint set (17) defines the binary variables.

5 Test problems

To illustrate the applicability of the mathematical formulation presented in this paper, two test instances for distribution networks with four tiers are examined. In the first instance representing a small-sized test instance, four manufacturing plants producing two products are incorporated. Product demands can be related to four customer zones. Furthermore, two potential central warehouses as well as three potential regional warehouses are taken into account. The second test instance represents a large problem incorporating two manufacturing plants, three locations of potential central warehouses, ten locations of potential regional warehouses as well as fifty customer zones. Forty products are considered. The decisions that have to be made in both instances regard the question where to implement assembly and packaging functions for enabling postponement in distribution networks. Potential locations are central and regional warehouses. Furthermore, implementations in factories are also incorporated. The latter case meets the traditional approach of distribution networks where only assembled and packaged products leave a factory.

The MILP problems were solved using CPLEX 8.1.0 in a reasonable time. After execution of a preprocessing, the first problem consists of 189 linear constraints with 458 linear and 29 binary variables as well as 1083 nonzeros. The linear objective function incorporates 487 nonzeros.

Using a Personal Computer (Pentium P4, 2.4 GHz, 1 GB main memory), the solution time is 0.016 seconds. The second problem includes 8506 linear constraints with 95200 linear and 48 binary variables as well as 284528 nonzeros. The linear objective function contains 93088 nonzeros, and the solution time on the same computer seems acceptable with 84.031 seconds.

The optimal solution of the first test instance is presented graphically. In Figure 4, the resulting distribution network is shown. The two numbers attached to the facilities as well as to the shipping links denote the quantity of flow regarding the two products taken into account. Both assembly and packaging (a+p) are postponed to the regional warehouses at the third tier. Thus, in virtue of the optimal solution semi-finished products have to be shipped from the factories to the central warehouses and from the central warehouses to the regional warehouses. However, this result depends highly on the applied data set. Some additionally tested data sets with different shipping, handling, assembly and packaging costs as well as different capacities result in totally different solutions regarding an optimal location of assembly and packaging activities.

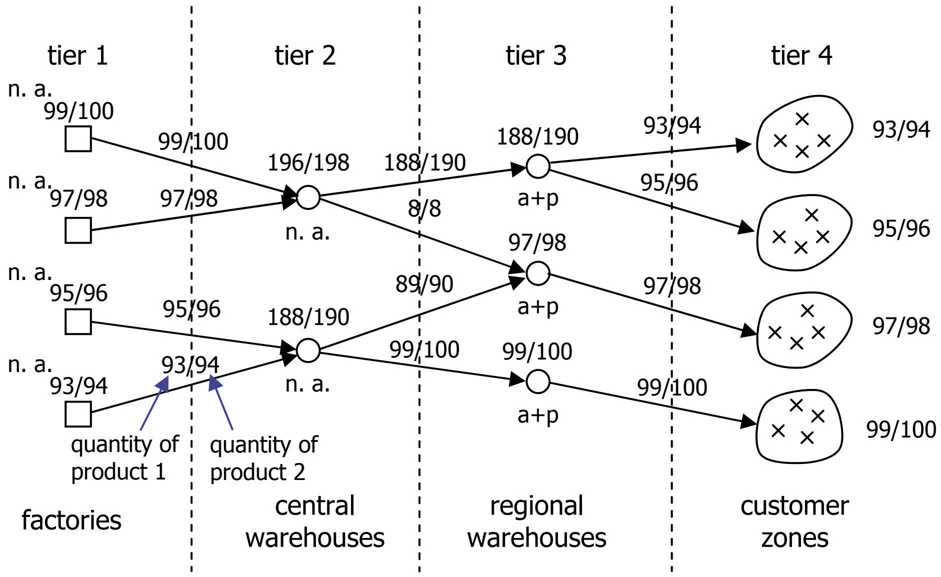

Figure 4: Optimal configuration of a distribution network (small-sized test instance)

6 Conclusions

In the presented paper the problem of designing a distribution network made up of four tiers taking into account aspects of postponement is studied. The developed mixed integer programming model enables the decision where to establish central and regional warehouses, where to implement potentially postponed functions for assembly and packaging in the distribution network and which quantities should be shipped from one facility to another one. Two scenarios are conceived and the corresponding test instances are solved.

The proposed model can be regarded as a basis for further research. Thus, several aspects should be taken into account in future work, e.g., nonlinearities of costs, diverse capacity levels, alternative technologies for shipping as well as processing in the facilities, an observation across several periods (dynamic model) and thus considering inventories, explicitly taking into account means of transportation, or capital commitment, risk, as well as insurance contributions. Moreover, implications of incorporating our model into advanced planning systems need to be explored.

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