Optimizing the Supply Chain Strategy of a Multi-Unit Finnish Nursery Company

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This paper introduces a capacitated mixed integer programming (CMIP) model for solving an integrated production-distribution system design problem (PDSDP) in the seedling supply chain management (SCM) of a multi-unit Finnish nursery company. The model was originally developed from a strategic perspective in which a company desires to evaluate the expansion or closure of its facilities. Nevertheless, the model is also used for solving operational and tactical level problems by applying applicable constraints. The data were collected from the company studied. The results proved that economies of scale could be exploited in seedling production more than the company does today; Compared to the company's current supply chain strategy with 5 nursery units producing seedlings, when other supply chain strategies were applied the number of nursery units decreased by 2–4 units, and cost savings in the supply chain varied from 11.3% to 21.3%.

Keywords mixed integer programming, optimization, economies of scale, seedling production, supply chain management
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1 Introduction

The nursery industry in Finland underwent two major changes during the 1990's. Firstly, the nursery industry was hived off from the state to incorporated companies, and the state-run price control of seedlings was stopped; and secondly, annual seedling demand decreased drastically from ca. 250 million seedlings to ca. 160 million seedlings today. These changes with increased import of seedlings from Sweden have led to explicit and increased competition in seedling markets. As a consequence of these changes, today's nursery managers are facing many challenges: customers, on the one hand, are requiring better quality, lower prices and more flexibility; and shareholders, on the other hand, are expecting better profitability.

The traditional thought, also in the nursery industry, is that there are so many conflicts in the multiple demands on the operations function that trade-offs are made in achieving excellence even in some of these dimensions (Erengüç et al. 1999). In the nursery industry, cost-effectiveness has, perhaps for historical reasons, usually been of secondary concern while more attention has been paid to biological issues. When changing this drawback to respond to current requirements, the development of supply chain management (SCM) plays an important role. Increasing the performance of the total logistic chain by developing SCM can also be seen from a larger perspective as providing a win-win situation for each participant in the supply chain (Slats et al. 1995, Aalto-Setälä 2000). For that reason, this study is noteworthy not only for nursery companies and their owners but also for forest owners' associations (FOAs) and forest owners aiming for profitable forestry.

Taking advantage of economies of scale is one of the essential principles in mass production (Uusi-Rauva et al. 2003) and has led to larger production units in many branches of industry (e.g. Beckenstein 1975, Pratten 1975, Ryti 1988, Aalto-Setälä 1998, Näsi et al. 2001). According to recent studies, it seems, if only implicitly, that Finnish nursery companies could also achieve advantages from economies of scale by centralizing production on fewer and larger nursery units (Petäjistö and Mäkinen 1999, Rantala et al. 2003a) and could also reduce costs by adapting a centralized system for planning of transportation (Rantala et al. 2003b). This study combines these aspects of SCM in an integrated production-distribution planning model. The model is built for solving problems which are basically derived from the fact that attempting to reach economies of scale in production leads to an increase in transportation costs. In the field of forest technology, similar problems have been examined, for instance, in the context of procurement of energy wood in which greater demand in a production unit requires a larger procurement area, thus increasing average procurement costs (Asikainen et al. 2001).

When such logistic models are designed, the planning problem is usually divided into three types of problems according to time horizons, namely operational, tactical and strategic problems (e.g. Chopra and Meindl 2001, Jang et al. 2002). In this paper, all of these perspectives are involved; the issues of production allocation can be regarded as operational planning (short-term) and capacity expansion as tactical level planning (mid-term), whereas the design of the distribution network is more strategic (long-term) in nature (e.g. Thomas and Griffin 1996, Erengüç et al. 1999). It should be noted that the aforementioned distinctions are not always clear, because some supply chain problems may involve elements that overlap different decision levels (Min and Zhou 2002). The integrated production-distribution system design problem (PDSDP) introduced in this paper was developed from a strategic perspective in which a company desires to evaluate the expansion or closure of its facilities. Despite that, the model constructed here can also be used to solve operational and tactical level problems by applying applicable constraints.

The most important solution approaches for supply chain problems are based on discrete mathematical programming and continuous approximations. The former approach relies on detailed data and numerical methods, whereas the latter relies on concise summaries of data and analytic models (Langevin et al. 1996). In this study, precise information on supply chain activities was available, and thus a mathematical programming approach was applied. The taxonomy of discrete approaches for PDSDPs can be presented, for instance, by dividing models according to type of objective function, number of echelons, number of products, existence of different capacity restrictions, certainty of demand and number of time periods. The majority of the prevailing models on this topic deal with cost minimization, although there are also a few profit maximization and multi-objective models (Dasci and Verter 2001).

Discrete approaches for integrated PDSDPs applicable to seedling SCM are presented, for instance, in Chandra and Fisher (1994), Jayaraman and Pirkul (2001), Jang et al. (2002). These articles approached PDSDP by applying mixed integer programming (MIP), which differs from general mixed integer linear programming by introducing one or more artificial variables that are restricted to be integers (e.g. Hillier and Lieberman 1974). Cohen and Moon (1991) presented an integrated MIP-based plant loading model with economies of scale and scope. In their model, the production cost function exhibits concavity with respect to production volume. This also

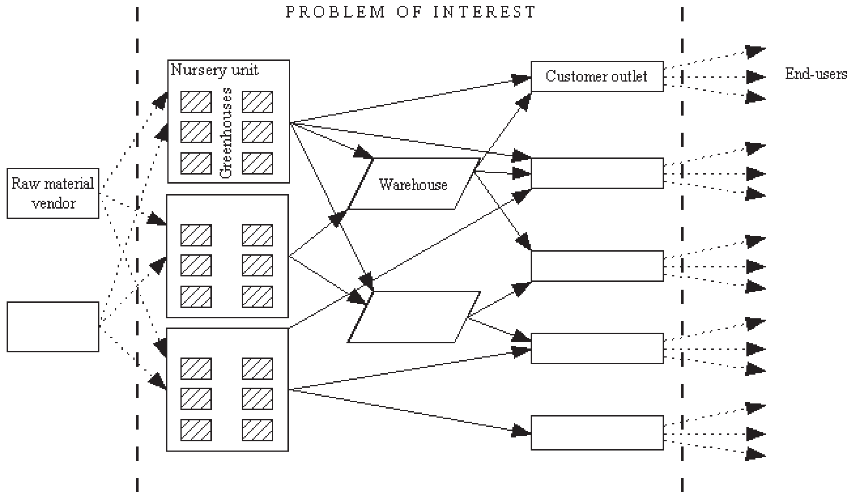

Fig. 1. Schematic illustration of a seedling supply chain.

makes sense in seedling production. In this paper, nursery labor costs are regarded as concave functions of production volume. Typically for MIP-based SCM models, economies of scale are also included in terms of the one-off setup costs of nursery units.

Optimization-based decision-making systems for greenhouse-production have been developed previously, for instance, in the lily flower business (Caixeta-Filho et al. 2002) and in potplant production (Saedt et al. 1991). The main objective of Caixeta-Filho et al. (2002) was to maximize the total contribution margin of the company studied due to optimizing the production variety of different plants by applying general linear programming. Saedt et al. (1991) developed an optimization model for transition from the firm's present production scheme towards the desired production scheme. The aim of this study is, in addition to introducing a tool for decision-making in seedling PDSDP, to demonstrate the consequences of different decisions on total production-distribution costs of a large-scale multi-unit Finnish nursery company.

2 Material and Methods

2.1 Problem Description

It is assumed that the problems concerned in this paper are generically feasible; i.e., the total nursery unit, greenhouse and frosty warehouse capacities are sufficient to satisfy the demand for seedlings. However, single nursery units and greenhouses as well as frosty warehouses have fixed capacities. The optimization problem modeled can, in general, be described as follows; forest owner's associations (FOAs) typically demand multiple seedlings of different seedling types, which are delivered to their outlets either directly from the nursery units or via frosty warehouses, which receive these products from several nursery units. Further delivery of seedlings from FOA outlets is assumed to be pre-determined; hence these outlets are regarded as final demand points. Seedlings are produced in greenhouses, which are located within the nursery units. The inbound costs of raw material transportation are ignored due to their minor importance in the total costs of the seedling supply chain. Certain seedling types are always delivered via frosty warehouses, whereas the others never are. Fig. 1 illustrates an example of the problem dealt with in this paper.

2.2 Parameter Definition

Values for input parameters are based on the experiences and accounting information of the company studied. Much of the data was gathered by interviewing nursery unit managers. Other sources used in data procurement were the company's depreciation plan, a list of fixtures and fittings, income and balance sheet statements and the customer database including past and current seedling orders. The geographical information system ArcView 3.2 with Network Analyst extension and a script wrote to find the shortest distances between different nursery units, between the nursery units and frosty warehouses and between these production and storing facilities and customer outlets were used to obtain information on transportation costs. In total, the problems dealt with here consisted of an SCM of ca. 20.7 million seedlings in the area of ca. 96 000 km^2.

The following assumptions were used in determination of *economical* parameters:

- Costs of opened nursery units are fixed.
- Only variable costs are associated with using frosty warehouses and existing greenhouses. Costs related to the use of existing greenhouses are treated as *convex* piece-wise linear functions. Convexity of the piece-wise linear function means that the most cost-efficient greenhouses are automatically utilized first while the minimization problem is at issue.
- Both fixed and variable costs are related to building new greenhouses.
- Transportation costs are treated as linear functions of transportation distance according to the observations of Rantala (2004).
- Labor costs are determined as *concave* piece-wise linear functions of production volume in which unit costs per seedling are assumed to be constant within production stages (t_j), such as $B_{(i+1)} - B_i$ (Fig. 2). Taking concavity into account when minimization problem is solved requires insertion of a few special constraints, which will be introduced in the next section (Eqs. 7.1 and 7.2). Originally, the differences in labor cost functions are caused by the existing differences among the facilities of different nursery units.

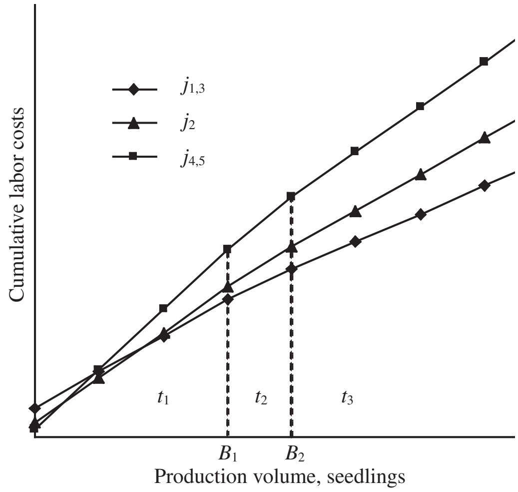

Fig. 2. Principles of concave cumulative labor cost functions for different types of nursery units (t_i = production stages 1...3, B_i = upper boundary of production stage t_i, j_i = nursery units 1...5)

The values of the *technical* parameters were based on the following facts:

- Different seedling types require different amounts of greenhouse area (p_i).
- Yield of acceptable seedlings delivered ahead from greenhouses differs between different seedling types (taken into account in calculation of p_i).
- Different seedling types require different volumes in a frosty warehouse. Volume is critical in warehousing because seedlings are packed before storing.
- Only a certain proportion (b_j) of the existing greenhouse area in each nursery unit is available for producing seedling types included in optimization (Table 1), with the exception of new greenhouses which capacity is included as a whole. Alternatives for new greenhouses were greenhouse types g_4 and g_6 (Table 1).
- Greenhouses are divided into two groups according to heating equipment. The capacity of those which can be heated is doubled due to the possibility to grow two crops per year (Table 1).
- Total land area available in a nursery unit for greenhouses can be restricted.

Table 1. Number of existing greenhouses (heated / total) of different types of greenhouses in the nursery units $j_{1...5}$ (b_j = proportion of the total existing greenhouse area available for producing seedling types included in optimization, $g_{1...6}$ = greenhouse types 1...6).

Nursery unit j	1	2	3	4	5	Total
b_j	0.95	0.95	0.95	0.95	0.80	–
g_1 (500 m^2)	0 / 9	0	0	0	0	0 / 9
g_2 (600 m^2)	0	0 / 2	0	0	0	0 / 2
g_3 (800 m^2)	5 / 8	3 / 12	8 / 9	3 / 6	7 / 7	26 / 42
g_4 (1000 m^2)	2 / 2	0	0	0 / 3	1 / 1	3 / 6
g_5 (1600 m^2)	0	0	0	0	2 / 2	2 / 2
g_6 (2000 m^2)	1 / 1	0	1 / 1	0	0	2 / 2
Total	8 / 20	3 / 14	9 / 10	3 / 9	10 / 10	33 / 63

2.3 Model Formulation

In this section, a capacitated mixed integer programming (CMIP) model for multi-echelon, multi-product, multi-plant seedling supply chain management (SCM) is introduced. In this model, locations of nursery units, frosty warehouses and customer outlets are considered to be fixed. In addition, customer demands are assumed to be constant. The model is static; all the decisions are made within a single period. In addition, all seedlings are assumed to be delivered to customers within a certain pre-determined time window; and thus, changes in production plan during the growing process are not allowed in this model. The following symbols and units of measurement are used in formulation of the model:

J refers to a set of nursery units, $\{j_1, j_2, ..., j_5\}$

W refers to a set of frosty warehouses, $\{w_1, w_2, ..., w_5\}$

G refers to a set of greenhouse types, $\{g_1, g_2, ..., g_6\}$

K refers to a set of customer outlets, $\{k_1, k_2, ..., k_{51}\}$

I^K refers to a set of seedling types delivered directly to customers, $\left\{i_1^K, i_3^K, i_5^K, ..., i_7^K\right\}$

I^W refers to a set of seedling types delivered via a frosty warehouse, $\left\{i_2^W, i_4^W, i_8^W, i_9^W\right\}$

H_g^E refers to a set of *existing* greenhouses of greenhouse type g, $\begin{cases} h_1^E, h_2^E, ..., h_9^E \mid H1 \\ h_{10}^E, h_{11}^E \mid H2 \\ h_{12}^E, h_{13}^E, ..., h_{53}^E \mid H3 \\ h_{54}^E, h_{55}^E, ..., h_{59}^E \mid H4 \\ h_{60}^E, h_{61}^E \mid H5 \\ h_{62}^E, h_{63}^E \mid H6 \end{cases}$

H_g^B refers to a set of *new* greenhouses of greenhouse type g, $\left\{h_1^B, h_2^B, ..., h_n^B\right\}$

T refers to a set of production stages, $\{t_1, t_2, t_3\}$

Input parameters, which values are given and considered as fixed in optimization, are denoted as follows:

D_{ik} demand for seedling type i^K or i^W by customer k

Technical parameters

M_w commensurate total capacity (throughput limit) of frosty warehouse w, [*seedlings/year*]

M_g commensurate total capacity of greenhouse h^E or h^B of greenhouse type g, [m^2*/year*]

N_j upper limit to greenhouse area that can be opened in nursery unit j, [m^2*/year*]

$EKAP_j$ total area of the *existing* greenhouses in nursery unit j, [m^2*/year*]

B_{tj} upper boundary of production stage t in nursery unit j, [*seedlings/year*]

p_i frosty warehouse space requirement coefficient for seedling type i^W

a_i greenhouse area requirement coefficient for seedling type i^K or i^W

b_j coefficient for total greenhouse area $EKAP_j$ that can be used for producing the seedling types included in the optimization

Economical parameters

Z total supply chain costs of the nursery company, [€]
F_j fixed cost for open nursery unit j, [*€/year*]
F_w fixed cost for open frosty warehouse w, [*€/year*]
F_{gh} fixed cost for building *new* greenhouse h^B of greenhouse type g, [*€/year*]
V_{gh} variable cost for utilization of greenhouse h^E or h^B of greenhouse type g, [*€/year*]
S_{tj} variable labor cost in production stage t in nursery unit j, [*€/seedling*]
C_{iwj} variable cost to transport a seedling of seedling type i^W from nursery unit j to frosty warehouse w, [*€/seedling*]
C_{ijk} variable cost to transport a seedling of seedling type i^K from nursery unit j to customer k, [*€/seedling*]
C_{iwk} variable cost to transport a seedling of seedling type i^W from frosty warehouse w to customer k, [*€/seedling*]

The following decision variables are also needed:

X_{ijtw} total number of seedlings of seedling type i^W produced in nursery unit j within production stage t and transported to frosty warehouse w, [*seedling/year*]
X_{ijtk} total number of seedlings of seedling type i^K produced in nursery unit j within production stage t and transported to customer k, [*seedling/year*]
X_{iwk} total number of seedlings of seedling type i^W stored in frosty warehouse w and transported to customer k, [*seedling/year*]
Q_j indication variable whether nursery unit j is opened
R_w indication variable whether frosty warehouse w is opened
P^E_{ghj} capacity utilization rate of *existing* greenhouse h^E of greenhouse type g in nursery unit j
P^B_{ghj} variable describing how many *new* greenhouses h^B of greenhouse type g are built in nursery unit j
A_{tj} indication whether production stage t is utilized in nursery unit j

The model aims to minimize the sum of costs to transport products to customers either directly from open nursery units or via open frosty warehouses and costs associated with producing and storing the seedlings. After the assumptions and notations given above, the model was formulated as follows:

Objective function (1)

Minimize $Z = [$

Production

$$\sum_j \Bigg(F_j Q_j + \sum_g \sum_h V_{gh} P^E_{ghj} + \sum_g \sum_h \left(V_{gh} + F_{gh}\right) P^B_{ghj} + \sum_t S_{tj}\left(X_{ijtw} + X_{ijtk}\right)\Bigg) + \tag{1.1}$$

Warehousing

$$\sum_w F_w R_w + \tag{1.2}$$

Transportation

$$\sum_{i^W}\sum_j\sum_t\sum_w X_{ijtw} C_{ijtw} + \sum_{i^K}\sum_j\sum_t\sum_k X_{ijtk} C_{ijtk} + \sum_{i^W}\sum_w\sum_k X_{iwk} C_{iwk} \ \Big] \tag{1.3}$$

Subject to

The total number of seedlings delivered to customers directly from nurseries plus those delivered via frosty warehouses must equal customer demand.

$$\sum_j \sum_t X_{ijtk} = D_{ik} \quad \text{for all } i^K \in I^K, t \in T \text{ and } k \in K \tag{2.1}$$

$$\sum_w X_{iwk} = D_{ik} \quad \text{for all } i^W \in I^W \text{ and } k \in K \tag{2.2}$$

Capacities of frosty warehouses must not be exceeded during the planning period. In addition, a warehouse must be open until it can be used.

$$\sum_{i^W}\sum_j\sum_t X_{ijtw}\, p_i \le R_w M_w \qquad \text{for all } w \in W \tag{3}$$

All seedlings stored in frosty warehouses must be delivered further to customers during the planning period.

$$\sum_j \sum_t X_{ijtw} = \sum_k X_{iwk} \quad \text{for all } i^W \in I^W \text{ and } w \in W \quad (4)$$

The greenhouse capacity available for seedlings included in optimization must not be exceeded. In addition, a greenhouse must be open until it can be used for production.

$$\sum_{i^K} \sum_{i^W} \sum_t \left(X_{ijtk} + X_{ijtw}\right) a_i \le M_g \left(\sum_h P^E_{ghj}\, b_j + \sum_h P^B_{ghj}\right) \quad (5)$$

for all $j \in J, w \in W, k \in K$ and $g \in G$

Greenhouses cannot be used unless the nursery unit they are assigned to is open. α is a large enough constant needed to ensure that Q_j equals 1 whenever any greenhouse P^E_{ghj} or P^B_{ghj} is used in production.

$$\sum_h \left(P^E_{ghj} + P^B_{ghj}\right) - \alpha Q_j \le 0 \quad \text{for all } g \in G \text{ and } j \in J \quad (6)$$

Labor costs are determined as concave piece-wise linear functions of production volume in nursery units. For that purpose, production volume is divided into production stages. The current stage is constrained by the stage capacity (Eq. 7.1), whereas the previous stages must be fully utilized and the later stages must not be allowed to produce anything (Eq. 7.2).

$$\sum_{i^K} \sum_{i^W} \left(X_{ijtk} + X_{ijtw}\right) \le \left(B_{(t+1)j} - B_{tj}\right) A_{tj} \quad (7.1)$$

for all $j \in J, t \in T, k \in K$ and $w \in W$

$$\frac{\sum_{i^K} \sum_{i^W} \left(X_{ij(t-1)k} + X_{ij(t-1)w}\right)}{B_{(t-1)j}} \ge A_{tj} \quad (7.2)$$

for all $j \in J, t \in T, k \in K$ and $w \in W$

The integrality restrictions for binary decision variables R_w and A_{tj} and the continuous decision variable P^B_{ghj} are imposed as follows:

$$R_w = \{0, 1\} \quad \text{for all } w \in W \quad (8.1)$$

$$A_{tj} = \{0, 1\} \quad \text{for all } t \in T \text{ and } j \in J \quad (8.2)$$

$$P^B_{ghj} \in Z_+ \quad \text{for all } g \in G,\ h \in H^B_g \text{ and } j \in J \quad (8.3)$$

whereas P^E_{ghj} is determined as follows:

$$0 \le P^E_{ghj} \le 1 \quad \text{for all } g \in G,\ h \in H^E_g \text{ and } j \in J \quad (8.4)$$

Non-negativity of the decision variables X_{ijtw}, X_{ijtk} and X_{iwk} is ensured due to the following constraints:

$$X_{ijtw} \ge 0 \quad \text{for all } i \in I^W, j \in J, t \in T \text{ and } w \in W \quad (9.1)$$

$$X_{ijtk} \ge 0 \quad \text{for all } i \in I^K, j \in J, t \in T \text{ and } k \in K \quad (9.2)$$

$$X_{iwk} \ge 0 \quad \text{for all } i \in I^W, w \in W \text{ and } k \in K \quad (9.3)$$

The goal of the optimization is to compute the optimal supply chain strategy with an optimal production plan on different planning levels. At first, the model is used for solving operational level problems. This can be done by setting decision variables Q_j (for all j) and R_w (for all w) equal to 1, and P^B_{ghj} (for all g, h^B and j) equal to 0. According to these settings, building new greenhouses or obtaining savings from closing nursery units are not allowed in the operational level solution. The solution of this experiment is further referred to as *OPER*.

The next step is tactical level planning. Here, the nursery units remain unchanged. However, if it is reasonable from the standpoint of cost-efficiency, more greenhouses can be built to increase the capacities of the nursery units. At this stage, a new constraint is introduced to ensure that total area available for greenhouses is not exceeded in any nursery unit (Eq. 10). The solution of this experiment is further referred to as *TACT*.

$$EKAP_j + \sum_h P^B_{ghj}\, M_g \le N_j \quad \text{for all } j \in J \text{ and } g \in G \quad (10)$$

As mentioned in the introduction, the model was originally constructed from a strategic perspective. Strategic level planning is the most far-reaching planning level. In a strategic level experiment the model is solved in its original form without any pre-determined variables. The solution of this experiment is further referred to as *STRAT*.

As mentioned above, the convex piece-wise linear function is used as a surrogate for the actual non-linear stepwise function describing the costs of using existing greenhouses to keep the model solvable within a reasonable computer time. To

Table 2. Main features, total costs and allocation of costs between transportation and production in different supply chain strategies. The total cost index for *OPER(CUR)* is 100.

Supply chain strategy	No. of nursery units producing seedlings	No. of frosty warehouses opened	No. of new greenhouses	Total cost index	Transportation costs, %	Production costs, %
OPER(CUR)	5	5	Not allowed	100.0	4.6	95.4
OPER	3	4	Not allowed	88.7	6.1	93.9
TACT	2	4	2	83.9	6.6	93.4
STRAT	1	5	10	78.7	8.6	91.4

evaluate the effects of this linearization on optimal solutions, Eq. 8.4 was replaced by Eq. 11 in the operational and tactical level computations. The effects of this replacement are estimated by comparing these results with *OPER* and *TACT*.

$$P_{ghj}^{E} = \{0, 1\} \qquad \text{for all } g \in G, h \in H_g^E \text{ and } j \in J \quad (11)$$

Differences between *OPER* and *TACT*, compared to *STRAT*, indicate the effects of constraints forbidding the building of new greenhouses and forcing the use of all existing nursery units on optimal solution. In addition to solving basic PDSDPs, sensitivity analyses of customer demand and transportation costs are included in strategic level experiments. To calibrate *OPER*, *TACT* and *STRAT*, they are compared to the current supply chain strategy (further referred to as *OPER(CUR)*) of the company studied. While computing *OPER(CUR)*, 98% of the production allocation among nursery units was pre-determined.

3 Computational Results

In this section, the model solutions are used to analyze different supply chain strategies (*OPER(CUR)*, *OPER*, *TACT* and *STRAT*) of the nursery company studied. Details of supply chain strategies are presented in the context of the model formulation. As mentioned, the piecewise linear function was used as a surrogate for an actual non-linear stepwise function describing the costs of using existing greenhouses. The effects of this linearization were estimated by solving operational and tactical level problems with and without linearization and by comparing these results with *OPER* and *TACT*. Differences in optimal solutions were only 0.08 and 0.02%, respectively. The difference would probably be even smaller in strategic level computations. Therefore, the accuracy of the model solutions presented below is not deteriorated markedly due to the linearization.

In general, the results proved that economies of scale could be exploited much more than the company does today in *OPER(CUR)*. At the first stage, the model was solved with applicable constraints for each planning level. In *OPER* and *TACT* the number of nursery units was constrained to equal to 5. As a result, all nursery units were opened, but production was allocated only among 3 (*OPER*) or between 2 (*TACT*) units (Table 2). Therefore, the fixed costs of the nursery units to which no production was allocated are omitted from the indexes of the optimal supply chain costs in Table 2. It should be noted, that the costs presented do not include any costs related to past investments, such as fixed costs of existing greenhouses. Of the existing 5 warehouses, the number of opened frosty warehouses varied between 4 and 5. A certain frosty warehouse was opened only in *OPER(CUR)*, in which its opening was pre-determined, and in *STRAT*.

As can be seen from Table 2, compared to *OPER(CUR)*, when other supply chain strategies were applied the cost savings varied from 11.3% to 21.3%. Moving from operational- to tactical- and ahead to strategic-level computations, constraints related to number of nursery units and building of new greenhouses were relaxed step by step resulting in fewer and fewer nursery units producing seedlings in the optimal solution. Simultaneously, transportation costs increased; but that was compensated by greater savings in production costs. All new greenhouses were type g_4 and built in nursery unit 1.

Table 3. Nursery unit-specific information in different supply chain strategies.

Nursery unit *j*	No. of production stages utilized	No. of seedlings produced	Labor unit cost index	Proportion of available greenhouse capacity used, %	No. of new greenhouses
OPER(CUR)					
1	2 / 3	8 670 000	100	72	Not allowed
2	1 / 3	2 107 000	143	39	Not allowed
3	2 / 3	8 083 000	102	96	Not allowed
4	1 / 3	822 000	188	18	Not allowed
5	1 / 3	1 000 000	179	13	Not allowed
OPER					
1	3 / 3	12 799 000	89	100	Not allowed
2	1 / 3	730 000	217	16	Not allowed
3	1 / 3	7 153 000	106	100	Not allowed
TACT					
1	3 / 3	14 508 000	86	100	2
3	1 / 3	6 174 000	110	88	0
STRAT					
1	3 / 3	20 682 000	79	100	10

Sensitivity analyses of demand and transportation costs were included in strategic level analyses. While the effects of changes in demand were studied, the constraints on frosty warehouse capacities had to be relaxed. As a result, in all solutions only a certain frosty warehouse was open. Compared to the original *STRAT*, the variations in demand studied here changed only a number of new greenhouses built in nursery unit 1 producing all seedlings. The variations were 25 and 50 percent increases and 25 percent decrease in total numbers of seedlings ordered by each customer and distributed equally among all seedling types. The numbers of new greenhouses built were 15, 20 and 5, respectively. *STRAT* was not sensitive to changes in transportation costs either; the number of nursery units opened to produce seedlings did not increase until the transportation unit costs were raised over four-fold.

Nursery labor costs made up 82.7–89.5% of the total supply chain production costs. Labor costs per seedling were 11.8, 17.4 and 29.6 percent smaller in *OPER*, *TACT* and *STRAT*, respectively, compared to *OPER(CUR)*. In general, the greater the number of seedlings produced in the nursery unit, the smaller was the labor cost per seedling (Table 3). Labor unit costs in nursery unit 1, for instance, decreased with respect to the increase in production volume, eventually being 21% lower in *STRAT* than in *OPER(CUR)*.

Allocation of the production of different seedling types among opened nursery units was observed from the solutions of different supply chain strategies. The allocation is interesting especially in operational and tactical level solutions (*OPER* and *TACT*), whereas in the current situation, *OPER(CUR)*, it is mostly pre-determined; and in *STRAT* all production is centralized to nursery unit 1 (Table 4).

Production of all small-sized seedling types, i_1, i_2 and i_9, requiring only a little greenhouse and transportation capacity was totally centralized to the nursery unit 1 already in *OPER*. Production of middle-sized seedling types i_4 and i_8, which were delivered via frosty warehouses, was distributed evenly between nursery units j_1 and j_3 located near opened large frosty warehouses. When moving from *OPER(CUR)* towards *STRAT*, production of middle-sized seedling types i_3 and i_7 was centralized more and more to nursery unit 1. Large-sized seedling type i_5 was produced in a widely distributed manner, whereas production of another large-sized seedling type i_6 was strongly centralized to nursery unit j_3, with the exception of *STRAT*.

All computations were performed with the What's Best! Industrial optimization solver in a PC with 260 MB RAM and a Pentium III pro-

Table 4. Allocation of the production of seedling types among open nursery units in different supply chain strategies. Values are percentages (%) of production in *OPER(CUR)* / *OPER* / *TACT* / *STRAT*.

Seedling type *i*	Nursery unit *j* 1	2	3	4	5
1	53/100/100/100	10/ 0/–/–	25/ 0/ 0/–	0/–/–/–	12/–/–/–
2*	24/100/100/100	0/ 0/–/–	37/ 0/ 0/–	0/–/–/–	39/–/–/–
3	45/ 85/ 93/100	22/ 0/–/–	33/15/ 7/–	0/–/–/–	0/–/–/–
4*	44/ 42/ 52/100	2/ 0/–/–	32/58/ 48/–	12/–/–/–	10/–/–/–
5	19/ 11/ 46/100	36/28/–/–	45/61/ 54/–	0/–/–/–	0/–/–/–
6*	11/ 0/ 0/100	9/14/–/–	69/86/100/–	0/–/–/–	11/–/–/–
7	66/ 83/ 91/100	0/ 0/–/–	34/17/ 9/–	0/–/–/–	0/–/–/–
8*	34/ 45/ 49/100	0/ 0/–/–	47/55/ 51/–	19/–/–/–	0/–/–/–
9*	57/100/100/100	0/ 0/–/–	43/ 0/ 0/–	0/–/–/–	0/–/–/–
Total, %	42/ 62/ 70/100	10/ 4/–/–	39/34/ 30/–	4/–/–/–	5/–/–/–
No. of seedling types produced	9/ 8/ 9/ 9	5/ 2 /–/–	9/ 6/ 6/–	2/–/–/–	4/–/–/–

* Delivered via a frosty warehouse

cessor running under Windows 2000 operating system. Computer times for finding *OPER(CUR)*, *OPER*, *TACT* and *STRAT* were 38, 85, 51 and 71 sec., respectively. While the use of existing greenhouses was determined according to Eq. 11, computer times for operational and tactical level problems were several hours.

4 Discussion

In general, the large-scale MIP-based network design problems are known to be difficult to solve (NP-hard (Non-deterministic Polynomial-time hard), in the technical sense) (e.g. Bixby et al. 2000). Owing to NP-hard problems, most of the methodological studies referred to include heuristic parts. In this study, the solving process was markedly accelerated by relaxing integer restrictions that ensure 0/1 utilization of existing greenhouses. As presented in the computational results, the effects of this relaxation were only marginal. For the sake of comparison, Gunnarsson et al. (2004) also observed very small gaps between the solutions of the LP-relaxation and the best integer solution found when a large-scale problem was at issue. Therefore, efforts to obtain mathematically exact solutions in this kind of seedling SCM problem would hardly be worthwhile.

The model was constructed primarily from the strategic perspective. Therefore the most valuable results are just those of strategic level computations instructing to design an optimal seedling supply chain in the long-run. The operational and tactical level solutions can be seen as intermediate points in the process of working towards a strategic level solution. Unquestionably, the company could achieve more advantages from economies of scale by centralizing production to fewer nursery units. The results also showed that the company has such an over-capacity of greenhouse area that the current production could be produced in fewer nursery units without any additional investment in new greenhouses than the company does today. This again supports the reasonability of the production centralization discussed earlier by Petäjistö and Mäkinen (1999) and Rantala et al. (2003a and 2003b). In any case, it should be noted that some special seedling types were excluded from the experiments. However, the proportion of these excluded seedling types was only about 12% of the company's production volume and has been decreasing year by year. The frosty warehouses were included in the experiments only to illustrate transportation costs as realistically as possible. Therefore, analyses of the cost-effects of using or closing frosty warehouses are only superficial.

The economies of scale achieved in labor costs are crucial in the results. While other labor intensive branches of industry have been studied, opposite results to those of this study concerning labor costs in production centralization/decentralization dilemma have also been obtained (e.g. Mariotti 1984, Crandall 1996). The difference between the results are mainly caused by the fact that in the Finnish nursery industry, labor unit costs are observed to decrease while the plant-specific scale increases, whereas Mariotti (1984) and Crandall (1996), for instance, proposed the opposite. In the Finnish nursery industry, from the standpoint of labor policy, the centralization strategy seems actually to be supported; it appears to be more difficult to find professional part-time employees for smaller nursery units than to find full-time workers for larger units. Labor unit costs in nursery units larger than any of today's units are, however, only estimates based on the data from existing nursery units of the company studied, views of nursery managers, observations made by Petäjistö and Mäkinen (1999) and experiences from larger foreign nursery units. The sensitivity of the optimization results to labor costs can be figured out due to the fact that within the previous accounting period, labor costs were ca. 50% of the company's turnover. It should be kept in mind that labor costs were here determined in accordance with current technical facilities in the nursery units. Therefore, the boundaries of production stages should be re-evaluated when, for instance, new investments are made in mechanization.

In practice, decisions concerning centralization of seedling production to a fewer large-scale nursery units cannot be made simply from the standpoint of cost-efficiency. Biological limitations and, on the enterprise level, also customer satisfaction perspectives must be taken into account. The biological limitations might be caused by chances of greater devastations by frost, diseases and pest insects, and restrictions on growing seedlings from applicable seed origins to a broader market area in more sparsely located large-scale nursery units. Nevertheless, there is no scientific evidence to support these suspicions. Biological requirements certainly create some framework for seedling production; but real obstacles seem to be unrealistic, especially when domestic production is at issue. Although there might be a risk of losing more seedlings at a time in larger nursery units, it seems that in practice the risk could be even reduced due to the advantages of economies of scale also in risk management. Current systems for controlling production, such as frosty storage, short-day and light treatments, on the other hand, enable seed origins from broader geographical area to be grown in the same place (Konttinen et al. 2000, Rikala 2002).

According to the follow-up study made by Rantala et al. (2003), the effects of distance and duration of transportation on the biological quality of seedlings are insignificant when seedlings are properly handled during transportation. From the perspective of customer satisfaction, some guesses have been made about the importance of localness for customers buying willingness. Nevertheless, it seems that today the most important competitive factor in the nursery industry is the price-quality ratio of seedlings and customer service in general. Evidence of that is the import of seedlings from Sweden to Finnish markets, in which case marketing acts have taken an edge over locality.

The company studied, like most other Finnish multi-unit nursery companies owned by state-aided institutions are just beginning to plan how to rationalize their supply chain activities. Thus, there is a set of minor problems to solve before the model can be validated empirically, not to mention the managerial implication of the optimization approach. For that reason, it might be more realistic at this stage to talk about theoretical possibilities for rationalization by applying the modelling technique introduced. Two assumptions should, in particular, be taken into account when the model is applied in practice; first, the availability of optimal transportation equipment was considered to be unlimited, which probably is not true in all remote districts where some nursery units are located; and second, the modes of operation in the nursery industry are quite indefinite, and it might be hard to get customer orders early enough to optimize all production-distribution operations at the same time. Nevertheless, in earlier optimization-based studies for greenhouse production, which included managerial implication of the models, similar results were obtained although the attributes measured were somewhat different; Saedt et al. (1991) and Caixeta-Filho et al. (2002) reported clear improvements in companies' financial results after implementation of an optimization-based decision support system.

This study was carried out in the operational environment of a Finnish nursery company. From the standpoint of SCM, the operational environments and organizations of the Finnish large-scale nursery companies are quite similar. Taking into account the fact that results were not very sensitive to changes in the initial data, e.g. in transportation costs, it seems that they can be generalized to the Finnish nursery industry as a whole. Thus, in summary, it seems that the total number of Finnish nursery units apparently is not, at least from the standpoint of supply chain costs, reasonable. From the perspective of Scandinavian seedling producers, the results might be seen as trendsetting, even though some operational differences exist, e.g. in organizational culture, labor issues and customer structures.

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