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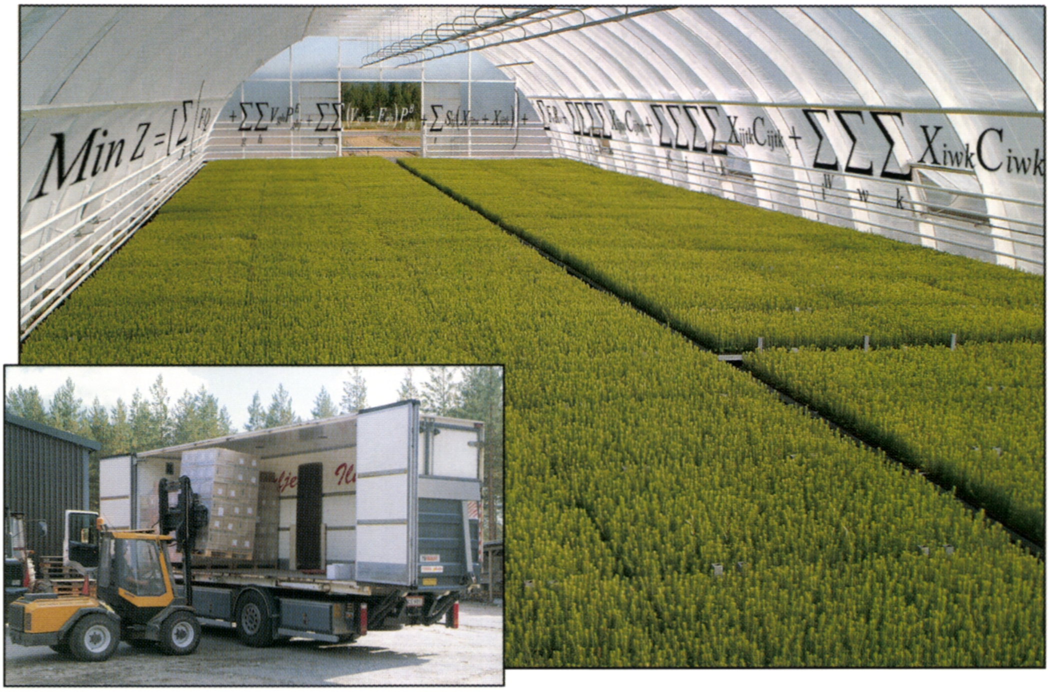

Models for designing the production-distribution system in supply chains of the Finnish nursery industry

Juho Rantala

Suonenjoen tutkimusasema - Suonenjoki Research Station

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Norway spruce seedlings in a greenhouse
in Suonenjoki Research Nursery (Erkki Oksanen, Metla).

Loading of a pickup truck with seedlings packed in cardboard boxes for
outbound transportation. (Taimitapio Inc.)

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Contents

Rantala, J. 2005. Models for designing the production-distribution system in supply chains of the Finnish nursery industry. Metsäntutkimuslaitoksen tiedonantoja 936. The Finnish Forest Research Institute, Research Papers 936. 64 p. + appendices.

This research introduces models for improving cost-efficiency in the production-distribution systems (PDSs) of the forest nursery industry. The primary research question is placed into the framework of the theories of logistics and economies of scale (ES). The main approach is operations research (OR), but the methods of work studies and business economics are also applied. As a result, the effects of different decisions related to production and distribution activities on costs of the PDS are quantified, and tools for managing these activities are introduced. The research was carried out in the operational environment of a Finnish nursery company. This dissertation summarizes, and partly complements, four scientific research articles cited as I, II, III and IV.

In Article I, the productivity and costs of packing seedlings and disinfecting seedling trays were studied in the mechanized packing-disinfection line. The economic rationality of the mechanization of the line was evaluated by comparing the observed costs to the corresponding costs of manual operation. In addition, sensitivity analyses were carried out to demonstrate, for instance, the effects of the interest requirement and the duration of the depreciation period on annual packing volume needed for economically profitable mechanization. The results indicated that the annual number of packed seedlings must be many times that of the study year before the unit costs with mechanization are lower than those for manual packing. In conclusion, it seems that most of the nursery units in Finland are still too small to gain a real advantage from ES by mechanizing production stages such as packing of seedlings.

In Article II, the management strategies used by the nursery company for transportation of seedlings were compared in different production strategies. To determine the optimal transportation plan, linear programming (LP) was applied. The relative improvement in cost-efficiency caused by the centralized transportation planning system (CTS) using LP, compared to the current decentralized transportation planning system (DTS), varied from 13.0 % to 36.5 %. In Article III, the applicability of LP in management of seedling transportation was compared to that of nonlinear mixed integer programming (MIP). The differences between models based on these methods, observed in the allocation of orders among nursery units, were small. Thus, in the actual business situation of Finnish nursery companies, LP seems to be an adequate tool for management of seedling transportation.

Article IV combines Articles I, II and III indirectly by introducing a capacitated mixed integer programming (CMIP) model for solving an integrated production-distribution system design problem (PDSDP). As a result, optimal production-distribution network of a nursery company is presented on different planning levels. The model was developed primarily from a strategic perspective but is also used for solving operative and tactical level problems. Compared to the company's current production-distribution network with five nursery units, the optimal number of nursery units decreased by 2–4 units depending on the planning level applied; and cost savings varied from 11.3 % to 21.3 %.

Altogether, the results showed that by centralizing production to a smaller number of nursery units ES could be utilized in seedling production more than the company does today. In this research, the rationality of the production centralization was not, however, studied from the standpoint of the nursery business as a whole. In general, increasing the performance of the total logistics chain by improving cost-efficiency of the PDS can be seen from a larger perspective as providing a win-win situation for each participant in the supply chain. For that reason, the results of this research are noteworthy, not only for nursery companies but also for forest owners and forest service providers such as forest owners' associations (FOAs) aiming for more profitable forestry.

Keywords: *economies of scale, logistics, seedling, optimization, operations research, transportation planning*

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Preface

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I'm thankful to many people for helping me with this dissertation. They have supported, encouraged and criticized me so that the outcome of my research work, including this dissertation, is much better than it would have been without their help. Special thanks go to my advisor Professor Pertti Harstela who helped me in many ways from the beginning of my work as research scientist to completion of this dissertation. Professor Harstela, together with Dr. Heikki Smolander, also arranged the financing of my work.

Many of my colleagues here at Suonenjoki Research Station (Metla) have helped me to see the research problems from a broader perspective: Mr. Nuutti Kiljunen commented the manuscript in many phases and helped to put it into the right framework, Mr. Veli-Matti Saarinen gave valuable comments on work studies and economic issues, Dr. Juha Lappi helped with optimization and programming issues and Dr. Risto Rikala advised me on biological issues. Actually, the whole personnel of Suonenjoki Research Station deserve acknowledgement for creation of a stimulating working environment. Professor Antti Asikainen (Metla, Joensuu Research Station) and Professor Jori Uusitalo (Faculty of Forestry, University of Joensuu) also gave valuable comments on this dissertation. I wish to thank Professor Anita Lukka (Lappeenranta University of Technology) and Dr. Dag Fjeld (Swedish University of Agricultural Sciences) for reviewing the manuscript. I also acknowledge CEO Jukka Nerg (Fin Taimi Inc.) for providing material and giving managerial perspective to the research process and Dr. Joann v. Weissenberg for checking the English language.

I thank my parents, Pirkko and Antti, and my grandparents for their endless support and positive encouragement of my career. My friends and siblings also deserve a word of thanks for keeping my thoughts away from scientific issues on free times. Finally, I thank my supportive and understanding wife, Minna-Riikka, for her empathy with me during the research process.

List of original articles

- **I** Rantala, J., Väätäinen, K., Kiljunen, N. and Harstela, P. 2003. Economic evaluation of container seedling packing and disinfection machinery. Silva Fennica 37(1): 121–127
- **II** Rantala, J., Kiljunen, N. and Harstela, P. 2003. Effect of seedling production and long-distance transportation planning strategies on transportation costs of a nursery company. International Journal of Forest Engineering 14(2): 11–19
- **III** Rantala, J. 2004. Linear programming and mixed integer programming in management of seedling transportation. International Journal of Forest Engineering 15(1): 41–51
- **IV** Rantala, J. 2004. Optimizing the supply chain strategy of a multi-unit Finnish nursery company. Silva Fennica 38 (2): 203–215

Author's contribution (Articles I and II):

In Article I, K. Väätäinen and N. Kiljunen were in charge of organizing the work study. P. Harstela participated both in planning the study and in writing the manuscript. J. Rantala analyzed the results, wrote most of the manuscript and submitted the paper.

Article II was planned in co-operation with all authors. In addition to helping plan the study, N. Kiljunen participated in constructing the model and writing the manuscript. J. Rantala carried out programming work, executed optimizations, analyzed results, wrote most of the manuscript and submitted the paper.

Abbreviations

CTS	centralized transportation planning system
CMIP	capacitated mixed integer programming
DTS	decentralized transportation planning system
DS	diseconomies of scale
ES	economies of scale
FOA	forest owners' association
GIS	geographical information system
IP	integer programming
LP	linear programming
LTL	less-than-a-truckload
MIP	mixed integer programming
NIPF	non-industrial private forest
OPER	optimal production-distribution network on operative level
OPER(CUR)	current production-distribution network
OR	operations research
PDS	production-distribution system
PDSDP	production-distribution system design problem
PQ	primary research question
PTGP	planting through the growth period
PWL	piece-wise linear
S1...S6	production strategies 1...6
SCM	supply chain management
$SQ_{1...6}$	secondary research questions 1...6
STRAT	optimal production-distribution network on strategic level
TACT	optimal production-distribution network on tactical level

1 Introduction

1.1 Background

During the 1990's, the Finnish nursery industry underwent huge changes. Firstly, the 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. 240 million seedlings to ca. 160 million seedlings. Simultaneously, few minor, at least from the perspective of seedling logistics, changes occurred in forest planting; container seedlings and spruce captured a large proportion of the market for bare-rooted seedlings and pine, respectively (Finnish Statistical... 2003). In particular, the aforementioned changes in the ownerships of the Finnish nursery industry and in the seedling demand together with increased import of seedlings from Sweden have led to explicit and increased competition in Finnish seedling markets. Consequently, 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.

Although the total number of large-scale nursery units in Finland has been decreasing moderately, today being slightly more than twenty (http://www.metla.fi/...), most of the units are still rather small, producing 3–10 million seedlings per year. Nursery units have mainly served local customers, and their production has been divided among many types of seedlings. For the sake of comparison, in Sweden, from which ca. 13.5 million seedlings are imported to Finland annually (Finnish Statistical... 2003), the total number of large-scale nursery units is about the same as in Finland but twice the number of seedlings is produced. About 80% of Finnish seedlings are produced by the large-scale nursery companies owned by state-aided institutions, ca. 10% by a forest industry company and ca. 10% by local small-scale producers (Petäjistö & Mäkinen 1999, Vuoden 2003 taimituotantotilastot... 2004). This research concentrates mainly on the large-scale companies owned by state-aided institutions.

In Finland, most of the seedlings produced by the large-scale nursery companies are delivered to non-industrial private forest (NIPF) owners via forest owners' associations (FOAs). Recently, changes in legislation concerning the seedling trade have led to changes in the role of middlemen such as FOAs, making them more responsible to the end-users for the quality of seedlings (Rikala 2002, Laki metsänviljelyaineiston... 2002). These legislative changes together with decreased overall numbers of FOAs and nursery units have led to the situation where an intermediate storage place appears to be a natural interface between the operations managed by a nursery company and the middlemen (Rantala 2003, Rantala et al. 2003). Therefore, in the remainder of this report the word "customer" refers to the middleman such as FOA, i.e. the direct customer of a nursery company.

1.2 Theoretical framework

1.2.1 Economies of scale and mechanization

As a consequence of the change from a "seller's market" to a "buyer's market" and accelerated technological developments, today's business is more strongly driven by competitiveness than ever before (Slats et al. 1995). In the industrial mode, firms compete in homogenous national markets with competitors having access to the same labor and capital sources as well as the same supplier base (Nahm et al. 2003). In general, environmental changes, such as international markets for products, increased market diversity and status of technology, are, however, moving competition from the industrial to the post-industrial stage. In the post-industrial stage more attention is often paid to economies of scope instead of economies of scale (ES), which was a dominant approach for increasing the level of activity at the industrial stage (Vonderembse et al. 1997, Vartia & Ylä-Anttila 2003, Nahm et al. 2003).

Nevertheless, there are a few weighty reasons for studying the ES in nursery industry; first, as mentioned in the previous chapter, the Finnish nursery industry has not thus far been driven by market forces and thereby might not be formed to operate in the most cost-efficient manner; and second, producing seedlings seems clearly to be mass-production. In addition, high-volume products such as seedling types are usually so similar and stable over time that differences between economies of scope and ES are only marginal. In the seedling business, changes in customer behavior also seem to be rather slow and easily predicted. These are typical indicators expressing a shift in competition from product performance to product cost (Skinner 1985, Vonderembse et al. 1997). In this situation, the advantages of ES are emphasized due, for instance, to possibilities for cost-efficient use of increasingly automated production processes (Vonderembse et al. 1997, Uusi-Rauva et al. 2003). Therefore, the Finnish nursery industry appears to be in a phase of development characterized still more by the industrial than the post-industrial stage, although some elements of the latter, such as import of seedlings, exist. For the reasons mentioned above, this research concentrates on studying ES, while the theories of product differentiation (see e.g. Beath & Katsoulacos 1991) and economies of scope are given minor attention.

Taking advantage of ES 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. Haldi & Whitcomb 1967, Beckenstein 1975, Pratten 1975, Ryti 1988, Aalto-Setälä 1998 and 2000, Näsi et al. 2001). In addition to production function, it is a well-known empirical observation that in many cases, transport rates fall with respect to the quantity of transportation, thereby producing a convex relationship between transport rates and the quantity shipped. This observation is normally termed ES in transportation (McCann 2001). Pratten (1975) defined ES very crudely as reductions in average costs attributable to increases in scale. ES are most commonly associated with the output of plants, but there are also numerous other dimensions of scale to which economies may relate. Pratten (1975) divided these dimensions into three classes: dimensions affecting the efficiency of production, dimensions affecting selling and distribution costs, and overall dimensions of scale.

The first dimension includes factors such as the total capacity of individual plants, the extent of standardization and the extent of vertical integration. The second dimension refers to attributes of customers such as sales to each customer and the geographic concentration of customers. The overall dimension of scale consists, for instance, of the size of the companies and the scale of an industry (Pratten 1975). From the standpoint of business operations, achieving greater ES in production allows prices of products to decrease. Price competitiveness, on the other hand, aims at reaching a greater share of the market, which in turn decreases production costs. In this type of market situation, the company with the greatest share of the market is also the most cost-efficient producer (Uusi-Rauva et al. 2003).

There are also factors, namely diseconomies of scale (DS), which increase average unit costs as scale increases, in some cases leading to multi-plant decentralization despite the existing product- and plant-specific ES. Pratten (1975) presented two groups of reasons for DS; the first exists while the supply of a factor of production is fixed or the cost of a factor increases as the demand for the factor rises; the second occurs while the efficiency in use of a factor of production declines as the quantity of the factor used by a company increases. In addition, while ES are aspired by centralizing manufacturing, the increase in distribution costs is usually an avoidable consequence (Mariotti 1984, McKinnon 1989, Uusi-Rauva et al. 2003) and can be seen as a source of DS (Beckenstein 1975). Thus the cost structure, i.e. proportions of procurement, production and distribution costs, of a product delivered to a customer and availability of factors of production, for instance, are important factors when it is decided whether to establish fewer multi-commodity plants or a greater number of focused plants (Lehtonen 2004).

Straightforward measurement of ES is usually not possible due to difficulties to describe processes in terms of engineering production functions that are based on scientific laws or experimental data (Pratten 1975). For this reason, quantification of both plant- and equipment-specific ES is often presented through examples of unit cost curves and discussion of break-even points. Nevertheless, Haldi & Whitcomb (1967) presented a simple method, which will be introduced in more detail in chapter 2.1, for analyzing the relationship between the costs and output dimension of scale for basic industrial equipment and operating costs of plants.

Manufacturers operating in an industrial environment usually seek better cost-efficiency by applying new technology, for instance, in mechanizing and automating production activities. In these cases, project (or productional investment) justification is usually based on anticipated reductions in costs (Nahm et al. 2003). Automation and integration of the production stages often occur sequentially, first creating islands of automation that are later integrated, or at least an attempt is made at integration (Vonderembse et al. 1997). The simple subsequent integration of all the separate optimal solutions does not necessarily lead to the optimal solution of the whole production-distribution chain. Therefore, when logistics chains are developed, a manufacturing engineering perspective should also be considered (Huang et al. 2000).

An example of a mechanized, and partly automated, part of the nursery industry process is packing of seedlings. The packing of seedlings meets several objectives: Seedlings may be packed for silvicultural reasons, to keep the seedlings in good condition during transportation and storing. On the other hand, the aim of packing is to minimize storage, handling and transportation costs. The latter standpoint is typical for distribution packing (Soroka 1999). In the Finnish nursery industry, seedlings have traditionally been packed manually; only in recent years have a few packing lines been mechanized. According to Landis et al. (1994), the aspects that should particularly be taken into account when the profitability of a certain piece of nursery equipment is evaluated are, for instance, low annual rate of capacity utilization and biological requirements. While approaching mechanization and automation in the context of development of forest harvesters, Harstela (2000) presented the following principles for cost-efficiency: Movements of machines are essentially quicker than manual ones, several work elements could be done simultaneously, many work functions and elements could be combined and done by one machine, multi-processing could be completed, continuous acting could increase efficiency, information technology could be exploited, quality of work could be improved, and good productivity, favorable cost ratio and high rate of utilization could be achieved. In addition, the technical availability should be sufficient.

1.2.2 Supply chain, logistics and production-distribution system

Logistics is about creating value – value for customers and suppliers of the firm, and value for the firm's stakeholders (Ballou 2004).

An abundance of definitions of supply chain, supply chain management (SCM), logistics and logistic management have been presented over time. Mentzer et al. (2001) summarized several authors and defined a supply chain as a set of three or more entities (e.g. organizations) directly involved in the upstream and downstream flows of products, services, finances and/or information from a source to a customer. Cooper et al. (1997) defined SCM as coordination of activities and processes within and between organizations in the supply chain that extends beyond logistics. Thus, SCM involves coordinating, integrating and redesigning of several elements such as locations, production, inventory and transportation (e.g. Davis 1993, Handfield & Nichols 1998, Chopra & Meindl 2003). Furthermore, SCM is based on the integration of all activities that add value to customers (Gunasekaran & Ngai 2004), so that merchandise is produced and distributed in the right quantities, to the right locations and at the right time, in order to minimize system-wide cost while satisfying service level requirements (Simchi-Levi et al. 2000). Mentzer et al. (2001) emphasized SCM's role in improving the long-term performance of the individual companies and the supply chain as a whole.

Logistics management, on the other hand, is the part of SCM that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements (Council of Logistics Management 2004). Thus, logistics is concerned more as a company's internal processes, whereas supply chain is a more holistic concept (Christopher 1998, Tan 2001). The traditional term logistics chain has also been defined as covering the material flow from raw material end to final customer end, and flows of demand information and transfer of payments in the opposite direction (Lukka 2004). Altogether, the modern view is that logistics is a subset in the supply chain (Harrison & van Hoek 2002, Ballou 2004).

There are three traditional stages in the supply chain: procurement, production and distribution (Thomas & Griffin 1996). The production-distribution link can take on many forms depending on the company's production and distribution strategies (Thomas & Griffin 1996). The role of production function is to fabricate the products that the company has sold (Lehtonen 2004). Distribution refers to the steps taken to transfer a product from production stage to customer stage (Chopra 2003, Karrus 2003). Furthermore, distribution can be divided into transportation and storing of products. Distribution is a key driver of the overall profitability of a firm because it directly impacts both on the supply chain cost and on the customer experience (Chopra 2003). Erengüç et al. (1999) divided the production-distribution link into supplier, plant and distribution stages. They also identified the relevant questions that need to be considered in jointly optimizing production-distribution planning decisions as a part of the entire supply chain network. The major questions in plant and distribution stages can be stated, for instance, as follows: What are the network configurations of the production processes and distribution channels? How many production places and distribution centers should be operated? Where should these facilities be located? Which product demands should be handled by each facility? (Erengüç et al. 1999). In this report, the production-distribution link is also examined from the standpoint of an individual production stage. Taking this into account, more comprehensive term production-distribution system (PDS) is used here to cover both production-distribution network configurations and aspects of individual production stages.

Bowersox & Daugherty (1995) introduced three logistics strategies: 1) Cost-minimization, where expense reduction is the overriding objective, 2) value-added maximization, where the focus is on finding the product attributes that will be most valued by the potential customers, and 3) control/adaptability enhancement, where the firm's attention is focused on a clearly defined market segment or particular buying group. According to Bowersox and Daugherty (1995), the aforementioned strategies are consistent with the famous value chain based enterprise strategies (cost leadership, differentiation and focused) introduced by Porter (1985). Fisher (1997) presented a dichotomy in the supply chain strategy between physically efficient and market-responsive strategies. In the dichotomy, the primary purpose of the physically efficient strategy is to supply a predictable demand efficiently at low cost, whereas that of market-responsive strategy is to respond quickly to unpredictable demand. In this research, the focus is on developing PDSs of the nursery industry on the basis of the strategies of cost leadership (Porter 1985), cost-minimization (Bowersox & Daugherty 1995) and physical efficiency (Fisher 1997).

Logistic chain modeling is very important in improving the overall performance of the total logistic chain (Slats et al. 1995). When logistic models are designed, the planning problem is usually divided into three types of problems according to time horizons, namely, operative, tactical and strategic problems (e.g. Jang et al. 2002, Chopra & Meindl 2003, Ballou 2004). The issues of production allocation are usually regarded as operative 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 & 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 & Zhou 2002).

The integrated production-distribution system design problems (PDSDPs) are often primarily developed from a strategic perspective in which a company wishes to evaluate the expansion or closure of its facilities. In many cases, PDSDPs are basically derived from the fact that attempting to reach ES by centralizing production leads to an increase in distribution costs. However, models constructed for solving PDSDPs can usually be used for operative and tactical level problems, too (e.g. Jayaraman & Pirkul 2001). The taxonomy of analytical 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 few profit maximization and multi-objective models (Dasci & Verter 2001). Vidal & Goetschalckx (1997) presented an extensive literature review of strategic production-distribution models.

Analytical approaches to logistic problems (including PDSDPs) rely mostly on traditional methods of operations research (OR) (Vidal & Goetschalckx 1997, Shapiro 2001, Chopra & Meindl 2003). According to Langevin et al. (1996), two important solution approaches for logistics and distribution problems are based on 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).

At present, mathematical programming seems to be the dominating approach for solving PDSDPs, although continuous models are also presented (Dasci & Verter 2001). Chandra & Fisher (1994), Jayaraman & Pirkul (2001) and Jang et al. (2002), for instance, approached PDSDP by applying discrete mathematical programming techniques. In this research, precise information on production-distribution activities was available, and thus a mathematical programming approach was applied.

1.2.3 Operations research

The OR approach came into being between the late 1940's and the early 1960's to help handle the increasingly complex problems of forecasting, coordinating, and controlling manufacturing operations (Skinner 1985). The goal of OR is to seek optimal, or at least good enough, solutions for many kinds of decision-making problems by applying various techniques and models (e.g. Taha 1992, Render & Stair 1992, Slats et al. 1995, Harstela 1998). The approach of OR is that of the scientific method. In particular, the process begins by carefully observing and formulating the problem and then constructing a scientific (typically mathematical) model that attempts to abstract the essence of the real problem. It is then hypothesized that the model is a sufficiently precise representation of the essential features of the situation, so that the solutions obtained are also valid for the real problem. This does not imply that the study of each problem must give explicit consideration to all aspects of the organization; rather, the objectives being sought must be consistent with those of the overall organization (Hillier & Lieberman 1974).

The terms OR and management science are often used synonymously. Asikainen (1995) summarized the views of some authors as follows: "OR can be seen as a more theoretical approach to complex operations and management science as the application of OR". Dykstra (1984) stated that there is no clear distinction between these two terms. As its name implies, OR involves "research on operations". OR is typically applied to problems that concern how to conduct and coordinate the operations or activities within an organization (Hillier & Lieberman 1974). When OR is applied, it seeks determination of the best course of action for the decision problem under the restriction of limited resources (Taha 1992). Slats et al. (1995) introduced the idea of dividing OR into mathematical and application-oriented (operation engineering) disciplines. Examined from this standpoint, this research concentrates on operations engineering that deals with the practical applications of OR.

Of the larger class of optimization techniques called mathematical programming, linear programming (LP) is by far the most widely used. According to McKinnon (1989), LP is an extensively used planning method also in distribution management. The advantages of LP are, for instance, short and fairly predictable solution times. LP typically deals with the problem of allocating limited resources optimally among competing activities (Hillier & Lieberman 1974). In more mathematical terms: LP is concerned with the problem of optimizing, i.e. either minimizing or maximizing, a linear function of several variables subject to linear constraints (Simonnard 1966).

The use of LP in mathematical programming is based on four assumptions, namely, proportionality, additivity, divisibility and deterministic assumption, which must all come true in the model formulation (Hillier & Lieberman 1974). To obtain solutions to LP problems involving two variables, the geometric approach might be used. However, for larger, practical-sized problems, the most widely used procedure is known as the Simplex method. This method is based on solving a system of linear equations with the Gauss-Jordan procedure (see e.g. Sposito 1975, Gass 1985). The Simplex method was also applied in this research, although there are currently some alternative techniques available.

Thomas & Griffin (1996), for instance, stated that models with linear transport costs might have limited application in practice. That is because the accuracy of linear models, e.g. LP models, might be debatable in some cases. This is due to the fact that in LP a linear objective and constraint functions are used in the formulation as surrogates for actual functions, which in transportation problems are often intrinsically nonlinear because they involve both fixed and variable costs. The process of converting a nonlinear expression to a linear one is called linearization. The effect of linearization on solution of an LP model can be evaluated, for instance, by constructing an optimization model with more realistic objective and constraint functions. Here, integer programming (IP) will be introduced.

IP models can be classified according to the types of variables; in pure integer programming, all variables are restricted to integer values; and in a mixed integer programming (MIP) formulation, certain variables are integers, whereas the rest are allowed to be continuous. Another classification criterion is the number of integer values allowed for single variables; binary (0/1) restrictions are used to indicate whether something happens or not, whereas general integer restrictions allow all integer values that are in a feasible solution area (Schrage 1997). There are two general approaches for solving IPs: cutting plane methods and the branch-and-bound method. The branch-and-bound method has thus far proven to be the most reliable; and most commercial IP codes use it, but aided by some cutting plane features, as was the case with the optimization solver used in this research (What's Best! 2000). In the most general terms, the branch-and-bound method is a form of intelligent enumeration (Hartley 1985, Schrage 1997).

In the context of IP models, good formulation is often crucial in determining whether the problem is solvable or not, and at least the solution time depends critically upon the formulation (Hillier & Lieberman 1974, Schrage 1997). Other important factors affecting solvability of the MIP problem and the time required to find the optimal solution are the type of software used and the options applied in simplifying, and due to that, accelerating the solution procedure (Bixby et al. 2000). Success in MIP usually relies on the use of specialized

MIP software rather than generalized IP software. Bixby et al. (2000) presented a snapshot overview of the developments and present state of solving LP and MIP problems.

It seems that mechanized planting, requiring planting throughout the growth period (PTGP), will increase in the future. The most important effect of longer planting period on seedling distribution is that whole orders of seedlings cannot be delivered to customers at the same time. Including a time factor in model is characteristic for dynamic optimization (e.g. Hillier & Lieberman 1974, Dykstra 1984, Chiang 1992). Nevertheless, the seedling distribution activities carried out by nursery companies are usually only a part, although the most wide-ranging, of the total distribution chain of seedlings. Therefore, as in most customer-oriented businesses, it is required that, to enable customers' success in the further delivery of seedlings and in the organization of planting work, seedling orders are delivered to customers during the predetermined time period. For that reason, in problems related to the effects of PTGP on transportation costs, transportation periods are assumed to be independent of each other; i.e. seedling delivery is not modeled as a dynamic problem.

Although OR techniques and models are potentially effective as a decision support tool for logistics, at present they are not fully applied in practice. According to Slats et al. (1995), the main reason for this is the lack of management awareness of the potential support provided by these OR techniques and models. This does not mean that OR techniques and models are never applied. However, the author is not aware of any forest nursery company using OR based models as a decision support tool in planning of activities contained in the production-distribution network.

1.3 State of the art research

ES and logistics in the forest nursery industry have been studied very little, and thus the literature is narrow. Although many possibilities appear to exist (Bare et al. 1984), neither has OR approach been in extensive use in nursery operations. However, some rather old studies exist: In Finland, Laakkonen (1978) presented an LP-based optimization model for production planning within a single nursery unit. Furthermore, to allocate regional demand for seedlings among existing nursery units, Laakkonen (1979) introduced a tactical level LP model. In this model, transportation distance (assumed to be twice the straight-line distance between the weighted central point of the market district and the nursery unit in model testing) affected transportation unit cost, which, however, was independent of transportation mode and capacity requirements of different seedling types. Jeffers (1965) and Grevatt & Wardle (1967) presented general models for nursery operations, which utilized both simulation and mathematical programming. In these papers, simulation approach was applied to model intra-nursery operations in order to find alternative nursery programmes including different production stages such as sowing (Grevatt & Wardle 1967) and storing of seeds and seedlings (Jeffers 1965). Mathematical programming, on the other hand, was used, for instance, to allocate seedling stocks among forest areas and to allocate seed lots to nursery units. Jeffers (1965) presented only a brief description of the properties of the proposed model, whereas Grevatt & Wardle (1967) introduced a simple cost-minimization model based on LP. Neither Jeffers (1965) nor Grevatt & Wardle (1967) quantified cost-effects of using the models.

Optimization-based decision-support 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 LP. Saedt et al. (1991) developed an optimization model for transition from the firm's present production scheme towards the desired production scheme. In addition, some sketchy studies with practical emphasis concerning improving efficiencies within the Australian forest nursery industry are summarized by Stephens (2003).

An example of a different approach to carrying out economic-oriented research in greenhouse production is presented by Hodges & Haydu (2000), who studied economic trends in Florida's ornamental plant industry by conducting industry surveys with mailed questionnaires. A mail-back survey procedure was also used by Brooker et al. (2000) to collect information on factors, for instance, limiting expansion and impacting price determination in the US nursery industry. In addition, Stegelin (1999) interviewed top-tier nursery managers' to clarify their conceptions of SCM and value chain management with bias on marketing in the US ornamental plant nursery industry. Furthermore, Stegelin (2000) divided the total cost of purchase into primary sources for creation of economic customer value in the ornamental plant industry.

Petäjistö & Mäkinen (1999) studied structures and success factors within the Finnish nursery industry. From this study, it can be concluded, if only implicitly, that greater ES might be achieved in the Finnish nursery industry by enlarging the size of production units. In the field of forest technology, ES has recently been studied, for instance, in the contexts of Finnish forest industry mergers (Kärri 1999), production technologies of the pulp and paper industry (Andrade 2000), procurement of energy wood (Asikainen et al. 2001), and the Swedish sawmill industry (Månsson 2003). With the exception of Asikainen et al. (2001), all of these studies reported some sort of existence of ES. Asikainen et al. (2001) observed DS in procurement of energy wood in which greater demand in a production unit requires a larger procurement area, thus increasing average procurement costs. Looked at from a wider perspective, Pulkki (2001) examined the role of SCM in forestry, and presented an example of the potential cost benefits gained by developing SCM in the context of pulp industry.

The antithesis between ES and DS in the context of plant-specific labor costs has been studied within many industrial branches in different countries. In some studies, DS, caused by powerful labor unions acting in larger production units and leading to lower labor productivity, have gained an edge over ES, which is obtained by the learning effect and more rationalized working methods (Mariotti 1984, Crandall 1996). In Finland, Halttunen (2004) observed that collective labor agreements were one of the greatest external barriers to growth of small and middle sized forest industry enterprises. Nevertheless, the results of research evaluating the specific effect of unions on productivity are mixed (Arthur & Dworkin 1991); and the evidence then is too inconsistent to draw any meaningful conclusions (Robbins 2001). Although labor productivity is of great importance in labor-intensive branches such as the nursery industry, in the Finnish nursery industry, the effects of labor unions are barely significant.

Different OR techniques are commonly used in research on various forest operations (e.g. Mikkonen 1983, Bare et al. 1984, Nieuwenhuis 1989, Steiguer et al. 2003). LP and its variations have been applied, for instance, to find optimal timber flows from procurement areas to mills (Williamson & Nieuwenhuis 1993, Palander 1997, Bergdahl et al. 2003, Forsberg & Rönnqvist 2003) and to model energy-wood flows (Palander et al. 2004). To obtain spatial information, LP model is often integrated to or at least used along with geographical information system (GIS). Pulkki (1984) developed a system based on the combination of a spatial database and heuristic programming for aiding decision-making in long-distance transport of wood. Lukka (1994) presented LP-based dynamic models for materials acquisition planning for the use of, for instance, the forest industry. From the standpoint of the objective of optimization, timber distribution is usually seen as a many-to-one problem, whereas seedling distribution is more like a reversed one-to-many problem. Nevertheless, they are methodologically somewhat analogous. IP has previously been used, for instance, in modeling the optimal use of log-stacking lift trucks at wood terminals (Heinämäki 1991). Mikkonen (1983) applied MIP as a tool for choosing the harvesting system. MIP has also been applied in optimization of transportation, storage and chipping of forest fuel (Gunnarsson et al. 2004).

1.4 Aims of the research

The traditional thought 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 Finnish nursery industry, cost-effectiveness has, perhaps for historical reasons, usually been of secondary concern. To overcome this drawback and to respond to requirements of present day business, economic-oriented development work is needed.

The principal aim of this research was to study the possibilities for improving the cost-efficiency of the PDSs in supply chains of the nursery industry, and to introduce tools for managing these logistical systems in large-scale nursery companies. The work focuses on exploring different dimensions of the PDS from the standpoint of ES. The primary research question (PQ) is derived from the principal aim as follows:

PQ: Could operational cost-efficiency of large-scale nursery companies be improved by reorganizing the production-distribution system (PDS) in terms of achieving greater economies of scale (ES)?

The answer to the PQ was initially explored in four scientifically reviewed research articles (I–IV) through the answers to the secondary research questions (SQs) presented below. This dissertation is a summary of those articles. However, some additional analyses are presented. In addition, terminology and symbols used in the original articles are standardized in this dissertation. Here, a slight mistake found in original Article IV (Eqs. 7.1 and 7.2) is also corrected (Eqs. 24 and 25).

In a case study presented in Article I, mechanized packing of seedlings and disinfection of seedling trays was investigated. The mechanized packing-disinfection line was chosen for two reasons; firstly, it is a typical example of mechanization in the nursery industry; and secondly, as a relatively expensive investment, it shows how cost-efficiency of a certain nursery production stage depends on the output dimension of scale. Here the aim was to find an answer to the SQ_1.

SQ_1: What are the means for improving cost-efficiency of seedling production by mechanization of production stages such as packing of seedlings and disinfection of seedling trays?

The hypothesis was that the mechanized line is more cost-efficient than manual packing and separate disinfection of seedling trays, if the following requirements are fulfilled: packing and disinfection operations are combined in the same line, the line speed is sufficient, the line is operationally reliable (technical availability), on the annual level there are complementary functions for production building and other expensive devices, and in particular, that the annual output of packed seedlings is high enough (rate of capacity utilization). The goals mentioned above apparently were fulfilled; so, based on these aspects, the line had potential for cost-efficient mechanization. Thus, the essential objective was to define the critical annual volume of production, i.e. the output dimension of scale, beyond which the mechanized packing-disinfection is cheaper than manual operation.

Articles II and III concentrated on the management of seedling transportation. In practice, the modes of operation in management of seedling transportation differ considerably. Thus, to quantify the consequences of different decisions concerning production and distribution strategies on transportation costs and to find the most applicable methods for managing transportation, a careful walkthrough of these modes and methods is needed. In Articles II and III, the SQs were formed as follows:

SQ_2: What are the cost-effects of different changes in seedling production strategy on the transportation costs of a nursery company?

SQ_3: Could the cost-efficiency of seedling transportation be improved by applying the OR approach compared to the current management system?

SQ_4: What is the applicability of the models based on linear programming (LP) and nonlinear mixed integer programming (MIP) for management of seedling transportation?

The aim of Article II was to quantify the effects of different seedling production strategies and transportation management systems on total transportation costs of the nursery company. The compared systems for transportation management were the current system with the company's internal transportations and the centralized planning system where an LP model is used to optimize transportation. In Article III, the main objective was to study the applicability of LP and MIP to management of seedling transportation in various business situations. Here, the effects of PTGP on transportation costs are also quantified. In addition, an MIP model for management of seedling transportation is introduced.

Article IV indirectly summarizes Articles I–III by introducing an integrated PDSDP. The aim of Article IV was, in addition to introducing a capacitated MIP (CMIP) optimization model for decision-making in PDSDP, to demonstrate the consequences of different decisions on the total production-distribution costs of a nursery company. Here, the SQs were stated as follows:

SQ_5: From the standpoint of cost-efficiency, what kind of production-distribution network would be optimal for a Finnish large-scale nursery company?

SQ_6: What kind of optimization model is applicable for solving the SQ_5?

Altogether, the results of the research (Articles I–IV) are examined, in particular, from the standpoint of economies of output dimension of scale. In general, increasing the performance of the total logistics chain can be seen from a larger perspective as providing a win-win situation for each participant in the supply chain (Slats et al. 1995). In addition, Aalto-Setälä (2000) observed that most of the benefits from ES were passed on to customers. For these reasons, the results of this research are noteworthy not only for nursery companies but also for forest owners and FOAs aiming for profitable forestry.

2 Materials and methods

2.1 Work study of mechanized packing of seedlings

Investigation of ES in the nursery industry was started with a work study of mechanized packing of seedlings and disinfection of seedling trays. For that purpose, the mechanized packing-disinfection line was studied. The approach selected was a time study combined with cost accounting. The method used in the time study was the work sampling method, which aimed at finding the percentual occurrence of a certain activity by statistical sampling and random observations (ILO 1979, Harstela 1991).

Video equipment was used to record the operation of the line. The recorded material consisted of the packing of Norway spruce (*Picea abies*) seedlings grown in 1260 units of Plantek 81F seedling trays (approx. 102 000 seedlings). The total number of seedlings packed during the study season was 1.6 million. The applied sampling interval was 2 minutes, and the total recorded work place time was 8 h 3 min. The percentual occurrences of different work elements, machine interruptions, idle times and rest pauses were recorded. Evaluation of the cost-efficiency of the line was based on cost accounting in which the observations of the work study were taken into account. Annual depreciation was calculated by the straight-line method. Only certain proportions of the fixed costs of devices, such as tractor and production hall, which were also used in other productive tasks, were allocated to the packing-disinfection line.

The simulation-based approach was excluded due to the compulsory working rate of the automated packing machine, which clearly determined the productivity of the line. The automated packing machine was a prototype, which was in operation for the first season. The theoretical impacts of increasing or decreasing the operation speed of the packing machine on productivity and unit costs were investigated for three different types of seedling trays. The most important difference between the trays was the number of seedlings per tray: 64, 81 or 121 (Lännen Plantek-F 2002).

Haldi & Whitcomb (1967) introduced a power function (see e.g. Sit & Poulin-Costello 1994), presented in Eq. 1, for estimating the relationship between the costs of a particular piece of equipment and its output dimension of scale.

$$C = aX^b \qquad \textbf{(1)}$$

In Eq. 1, C represents cost, X output capacity, and a is a constant; the exponent b is the scale coefficient. The parameter b controls the shape of the curve. A value of $b < 1$ implies increasing returns to scale, $b = 1$ shows constant returns, and $b > 1$ implies decreasing returns. In this dissertation, the results of Article I were complemented by fitting the total cost/output data of the packing-disinfec-

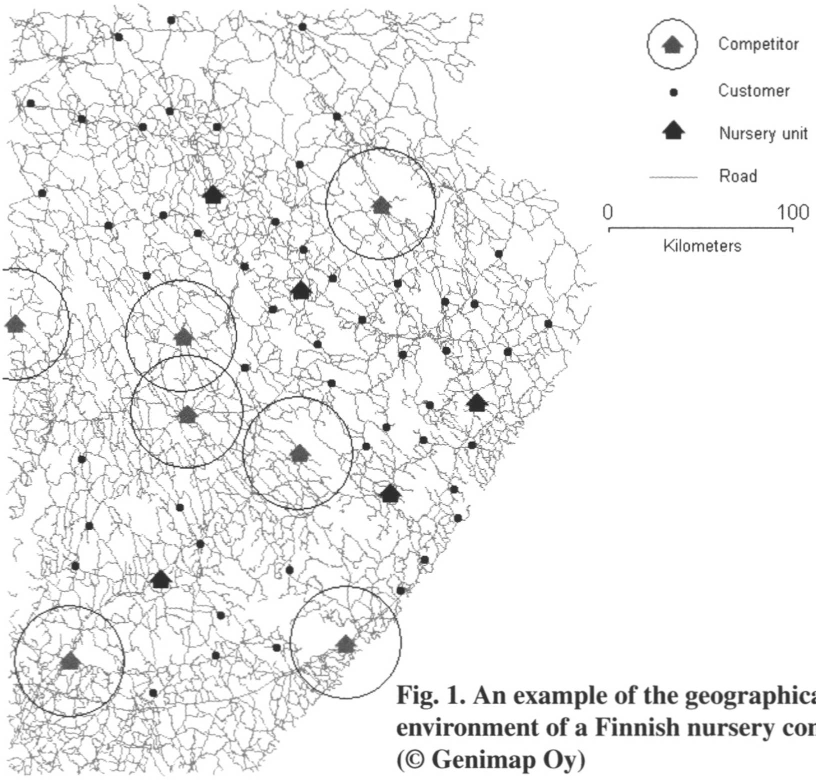

Fig. 1. An example of the geographical environment of a Finnish nursery company. (© Genimap Oy)

tion line to Eq. 1 to compare the observations with those of Haldi & Whitcomb (1967). In addition, sensitivity analyses of interest requirements and durations of depreciation period set to the packing-disinfection line investment as well as to an additional investment, for instance, in replacing a worker in the line were included in this dissertation although they were not reported in Article I.

2.2 Characteristics of the production-distribution system

The production-distribution network consisted of the main marketing area (ca. 96 000 km^2) of the Finnish multi-unit nursery company including locations of its nursery units, a vector-based network of main roads and locations of customers (Fig. 1). In addition, locations of nursery units owned by competitive seedling producers were taken into account in Articles II and III. In these Articles (II and III), customers located closer than 30 km to any nursery unit were supposed to pick up their seedlings themselves rather than having them delivered, and were thus excluded from the experiments. The spatial data were managed by a GIS.

The modes of operation in the Finnish nursery industry can be described briefly as follows: FOAs typically demand multiple seedlings of different seedling types, which are delivered to their outlets either directly from the nursery units or via

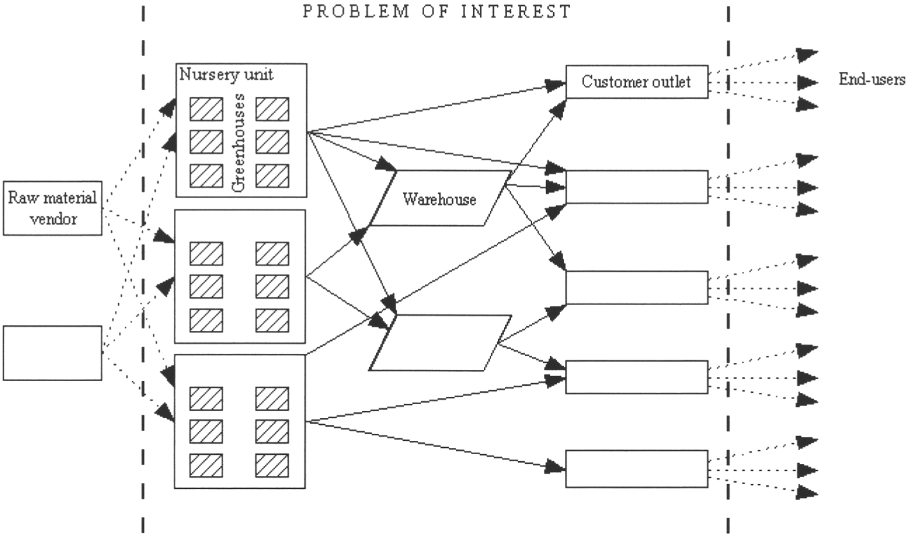

Fig. 2. Schematic illustration of a supply chain of seedlings.

frosty warehouses, which receive these products from several nursery units. In this research, further delivery of seedlings from FOA outlets to end-users is assumed to be pre-determined; and hence these outlets are regarded as the final demand points. Seedlings are produced in greenhouses, which are located within the nursery units. The inbound costs, such as transportation of raw material, are ignored due to their minor importance in the total logistics costs of the nursery company. Certain seedling types are always delivered via frosty warehouses, whereas others never are.

In practice, the principles of distribution network design used most of all in supply chains of the Finnish nursery industry are somewhat similar to the option of "distributor (e.g. FOA) storage with last-mile delivery to end-users (NIPF owners)", among others presented in Chopra (2003). Fig. 2 illustrates an example of the seedling supply chain dealt with in this research. The echelon of warehouses is included only in Article IV.

All experiments included in this research were done in the operational environment of the same Finnish multi-unit nursery company. The materials used in Articles II–IV were alike, even though there were some differences in demand parameters; first, the customer-specific orders were the same in Articles II and III but differed slightly from those in the Article IV; second, in Articles II and III, a variety of seedling types was compressed to the five most important types included in optimizations, whereas in Article IV only four types of seedlings were included; and third, the locations of customers were the same in Articles II and III but differed slightly from those in Article IV. These differences were caused by the lack of precise data on seedling demand during data collection for Articles II and III, whereas Article IV was based on actual data of the company

Table 1. Summary of the seedling production strategies used in Articles II–III.

Production strategy (reference to articles)	S1 (II, III)	S2 (II)	S3 (II, III)	S4 (II)	S5 (II)	S6 (II, III)
No. of nursery units	5	5	3	3	3	1
No. of seedling types produced in a nursery unit	5	4–5	5	3–5	2–3	5
Degree of product specialization	None	Small	None	Medium	High	–

studied. In both cases, however, the material included 51 customers and the seedling demand per customer varied between 100 000 and 1 100 000 seedlings, the average being about 500 000.

The production strategies (S1...S6) used in Articles II and III were chosen by the authors based on the views of the company managers. The dimensions of the production strategies were included in terms of the number of nursery units (Articles II and III), the degree of production specialization among nursery units (Article II), and the allocation of transportation among different numbers of time periods (Article III). A summary of the production strategies included in Articles II and III is presented in Table 1.

In S1 and S3 all nursery units produced equal numbers and proportions of the five seedling types, i.e. the balanced production system was at issue. In S6 the whole production was centralized to one large nursery unit. These strategies (S1, S3 and S6) are rather theoretical situations. S4 and S5, on the other hand, describe potential situations in the near future. In S2, five nursery units produced seedlings according to the current practice of the company studied. The latter strategies (S2, S4 and S5) are so-called unbalanced production systems. In all production strategies, the total number of seedlings produced was the same. In the strategies with less than five nursery units, the current five units were assumed to remain as sale and depot locations, although production there was abolished.

The production strategy dimension of dividing transportation into time periods independent from each other, studied in Article III, is derived from the assumption that in the future PTGP will become more general. Criteria for allocating transportation among different periods, which reflects a possible situation in the future, were based on recent studies (Luoranen 2000, Luoranen et al. 2001, Helenius et al. 2002) and on the views of the author and professionals in silvicultural operations. In the three-period model the proportions allocated to periods 1...3 were 53%, 31%, 16% of the total seedling orders, respectively, whereas in the five-period model the proportions allocated to periods 1...5 were 39%, 21%, 19%, 13% and 8%, respectively.

To obtain information on seedling transportation practices, nursery managers, FOA officials and third-party transport company managers were interviewed. The information gathered was used to estimate transportation costs and the seedling type specific capacities of different transportation vehicles. Total transportation costs consisted of three types of costs: fixed, variable and terminal. The fixed costs, i.e. the non-variable costs of ownership for the vehicles, were calculated on the assumption that the external transportation company owned the vehicles used for transportation. Thus, only a certain part of the fixed costs was assigned to seedling transportation. The terminal cost represented the cost of activities related to loading seedlings for transportation in nursery units and unloading them at customer locations. The variable cost was the constant cost-coefficient for a certain distance unit transported by a certain vehicle.

In Article IV, the most essential cost material was related to production activities. Here, the values for input parameters were based on the experiences and actual accounting information of the company studied. Much of the data was gathered by interviewing managers of the nursery units. 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, which included past and current seedling orders.

The following assumptions were used in determination of *economic* parameters (Article IV): The costs of the opened nursery units are fixed, only variable costs are associated with using frosty warehouses and existing greenhouses, both fixed and variable costs are related to building new greenhouses, transportation costs are linear functions of transportation distance, and there are both fixed and variable labor costs. The values of the *technical* parameters were based on the following facts: Different seedling types require different amounts of greenhouse area, yield of acceptable seedlings delivered ahead from greenhouses differs among seedling types, different seedling types require different volumes in frosty warehouse, only a certain proportion of the existing greenhouse area in each nursery unit is available for producing seedling types included in optimization, there are two alternatives for the type of new greenhouse, existing greenhouses are divided into two groups according to heating equipment, and total land area available in a nursery unit for greenhouses can be restricted.

2.3 Optimization techniques applied

In Article II, LP is used to optimize seedling transportation of the nursery company in various production strategies. The topics studied in these experiments were the effects on transportation costs of managing transportation by a centralized transportation planning system (CTS) using LP instead of the current decentralized transportation planning system (DTS). In DTS, transportation is organized by the nursery unit from which the customer has ordered seedlings. In practice, DTS leads to a situation where, due to difficulties in growing seedlings economically to meet the demand in a certain market area, internal transportation is needed between the nursery units of the company. When LP is applied for this type of transportation problem, transportation cost functions must be linearized. Here, linearization means that the unit costs of transportation were based on full vehicle loads and were thus independent of the number of seedlings transported. To study the effect of linearization on the optimal solutions obtained with the LP model, IP, and in particular MIP, was applied. In the MIP model introduced in Article III, variables describing vehicle loads were restricted to get general form integer values.

This paragraph illustrates how LP and MIP models differ from each other in solving an optimization problem such as that of seedling transportation. Obviously, the accuracy of the LP model deteriorates whenever the optimal solution includes such a number of seedlings transported to a certain customer that do not fit exactly into full vehicle loads. While the number of customers remains constant, a decrease in the total number of seedlings delivered will decrease the average number of seedlings transported to each customer. The smaller the number of seedlings transported to a customer, the larger can be the relative difference in the unit cost per seedling between the LP and MIP models. This effect can be illustrated by examining the worst possible (the highest unit cost) solution for the MIP model: Let the number of seedlings transported to *m* customers be *N*. The average number of vehicle loads transported to a customer is denoted by *a*, and L_h is the transportation capacity for vehicle *h*. At first, *N* can be determined as follows (Eq. 2):

$$N = a\,m\,L_h \tag{2}$$

The worst solution for the MIP model will be achieved by transporting one seedling to *m–1* customers and the rest of the seedlings to customer *k*. Taking Eq. 2 into account, the highest transportation unit cost u_{hjk} (*j* refers to nursery unit) for the MIP model can be stated according to Eq. 3. The ceiling function (⌈ ⌉) is used to round the number up to the next integer value.

$$u_{hjk} = c_{hjk}\left\lceil \frac{(m-1)+\left\lceil \dfrac{amL_h - m + 1}{L_h} \right\rceil}{amL_h} \right\rceil \tag{3}$$

In Eq. 3, c_{hjk} indicates the full-load transportation cost without a terminal cost. The corresponding unit cost u_{hjk} for LP model can be calculated by subtracting the terminal unit cost (r_{hi}) for seedling type *i* transported by vehicle *h* from the unit cost (c_{hijk}) for seedling type *i* transported from nursery unit *j* to customer *k* by vehicle *h* according to Eq. 4.

$$u_{hjk} = c_{hijk} - r_{hi} \tag{4}$$

Determination of the transportation unit costs in the LP and MIP models is presented in Fig. 3, which also illustrates the principal difference between the models. In both models, terminal costs are treated as linear and are thus not included in this demonstration.

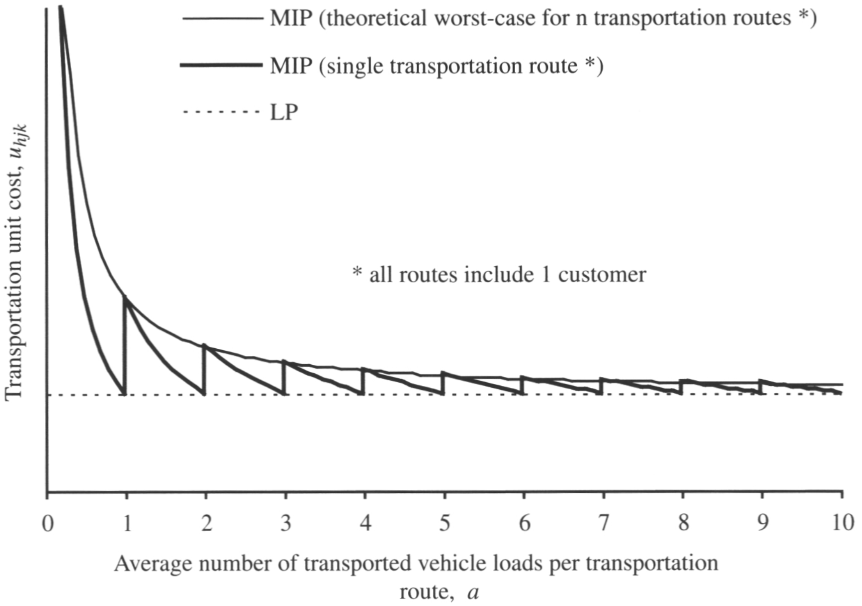

Fig. 3. Principal unit cost functions of the LP and MIP models for a single transportation route and the theoretical worst solution function for n transportation routes optimized with the MIP model.

In constructing an integrated production-distribution model to solve PDSDP in the supply chain of a nursery company (Article IV), elements from both LP and MIP are applied; variables related to transportation activities are treated as linear, whereas in modeling of production both linear and nonlinear variables are involved. Here, nonlinear variables are restricted to get only binary (0/1) values. In this context, processing of *concave* and *convex* functions as parts of the optimization model is needed to describe production cost factors correctly.

Cohen & Moon (1991) presented an integrated MIP 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 makes sense in determination of the cost functions for nursery labor needed in seedling production. Therefore, labor costs are determined here as *concave* piece-wise linear (PWL) functions of production volume. In PWL functions the unit costs per seedling are assumed to be constant within production stages t_i such as $B_i - B_{(i-1)}$ (Fig. 4). When the minimization problem is at issue, taking concavity into account requires insertion of a few special constraints. These constraints will be introduced in Chapter 2.4 (Eqs. 24 and 25).

Parameters used for labor costs derived from labor productivities in nursery units are based on observations of labor productivity in the current nursery units of the company studied, on experiences from foreign large-scale nursery units and on the views of the author and the nursery managers. In determination of

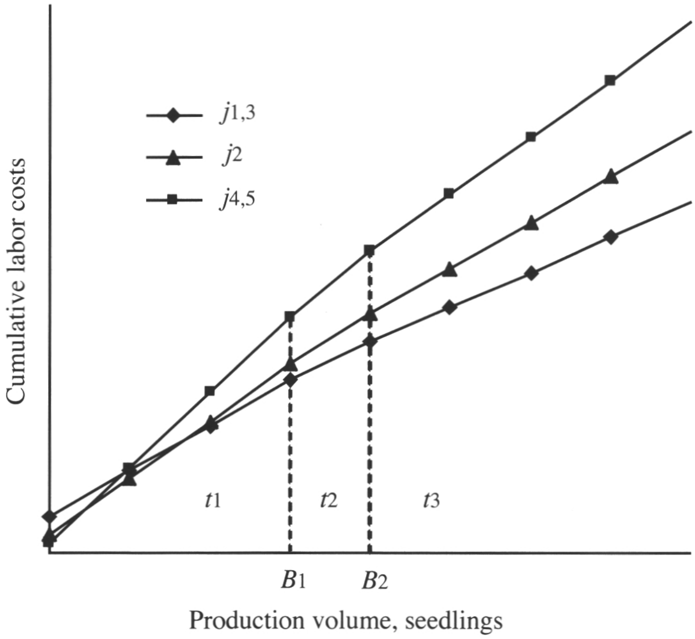

Fig. 4. Principles of concave cumulative labor cost functions for different types of nursery units (t_i = production stages 1...3, B_i = upper boundary of production stage t_i, j_i = nursery units 1...5)

labor productivity values, the current level of mechanization, according to which fixed costs for nursery units are determined, is assumed.

In addition to concave labor cost functions, ES are included in the MIP-based integrated production-distribution model in terms of the one-off setup costs of nursery units. Set-up costs are concerned as a fixed-charge problem (see e.g. Hillier & Lieberman 1974). Here, a special constraint (Eq. 23) is needed to ensure that the decision variable describing whether a nursery unit exists or not will take on correct values. The variable costs related to the use of existing greenhouses in nursery units are treated as *convex* PWL functions. Convexity of the PWL function means that when the minimization problem is at issue, the most cost-efficient greenhouses are automatically utilized first.

2.4 Formulation of the models

In this section, three distinct optimization models are presented; firstly, the LP model is introduced for optimizing seedling transportation; secondly, the MIP model is constructed for the same purpose to evaluate effects of linearization on the LP model solution and to study the effects of dividing transportation into time periods on transportation costs; and thirdly, the CMIP model is introduced to solve the PDSDP. The objective of all models is to minimize costs at issue.

It is assumed that the problems dealt with here are generically feasible; i.e., the total nursery unit, greenhouse and frosty warehouse as well as transportation capacities are sufficient to satisfy the demand for seedlings. However, unless mentioned otherwise, single nursery units and greenhouses as well as frosty warehouses have fixed capacities. In experiments with linear transportation costs (Articles II and IV), the capacities of transportation vehicles are included only by taking them into account in determination of transportation costs, whereas in the experiments with integer restrictions on variables describing the number of transported loads (Article III), vehicles are treated one by one, each being capacitated.

The following symbols and units of measurement are used in formulation of LP and MIP models. It should be noted that the symbols used in both models are standardized here and thus differ from those in the original articles (II and III).

t	refers to the transportation period
h	refers to the transportation vehicle
i	refers to the seedling type
j	refers to the nursery unit
k	refers to the customer
Z	total transportation costs of the nursery company, [€]
c_{hijk}	unit cost for seedling type *i* transported from nursery unit *j* to customer *k* by vehicle *h*, [€/*seedling*]
c_{hjk}	full-load transportation cost without terminal cost from nursery unit *j* to customer *k* by vehicle *h*, [€/*load*]
r_{hi}	terminal unit cost for a seedling of seedling type *i* transported by vehicle *h*, [€/*seedling*]
f_{hi}	fixed unit cost for a seedling of seedling type *i* transported by vehicle *h*, [€/*seedling*]
v_{hi}	variable unit cost per unit of distance for a seedling of seedling type *i* transported by vehicle *h*, [€/*(seedling*km)*]
r_h	full-load terminal cost for vehicle *h*, [€/*load*]
f_h	fixed cost per load for vehicle *h*, [€/*load*]
v_h	variable cost per unit of distance for vehicle *h* [€/*(load*km)*]
s_{jk}	to-and-fro transportation distance from nursery unit *j* to customer *k*, [km]
x_{hijk}	number of seedlings of seedling type *i* transported from nursery unit *j* to customer *k* by vehicle *h*, [*seedlings*]
x_{thijk}	number of seedlings of seedling type *i* transported from nursery unit *j* to customer *k* during transportation period *t* by vehicle *h*, [*seedlings*]
d_{ik}	number of seedlings of seedling type *i* ordered by customer *k*, [*seedlings*]
d_{tik}	number of seedlings of seedling type *i* ordered by customer *k* during transportation period *t*, [*seedlings*]
S_{ij}	production capacity of seedling type *i* in nursery unit *j*, [*seedlings*]
l_{thjk}	number of loads transported from nursery unit *j* to customer *k* by vehicle *h* during transportation period *t*, [*loads*]
P_h	commensurate transportation capacity for vehicle *h*, [*seedlings/load*]
p_i	space requirement coefficient for a seedling of seedling type *i*

After the notations given above, the standard LP model for optimizing seedling transportation is formulated as follows:

$$Minimize\ Z = \sum_h \sum_i \sum_j \sum_k c_{hijk} x_{hijk} \tag{5}$$

Where

$$c_{hijk} = r_{hi} + f_{hi} + s_{jk} v_{hi} \tag{6}$$

Subject to

Non-negativity:

$$x_{hijk} \geq 0 \quad \text{for all } h, i, j, k \tag{7}$$

Customer orders:

$$\sum_h \sum_j x_{hijk} = d_{ik} \quad \text{for all } i, k \tag{8}$$

Production of seedling types in the nursery units:

$$\sum_h \sum_k x_{hijk} \leq S_{ij} \quad \text{for all } i, j \tag{9}$$

To compare the applicability of MIP and LP to optimization of seedling transportation in various business situations, the MIP model was built. The main difference between the models is that in the LP model the optimal transportation cost is a multiple of the theoretical cost per seedling, whereas in the MIP model the cost-effects of less-than-a-truckload (LTL) shipments are taken into account by restricting the number of transported vehicle loads to get integer values. In addition, in the MIP model the terminal costs are assumed to increase linearly as a function of the transportation capacity used, which can be seen in the latter part of the objective function (Eq. 10). Actually, the LP model presented above is a special case of the MIP model; in the LP model the ratio between the sum of the space requirement for all seedlings in a certain vehicle load and the commensurate transportation capacity of the vehicle is always assumed to equal 1. The MIP model is formulated as follows:

Objective function – minimizes the total variable and fixed costs of all vehicle loads plus the sum of terminal costs associated with all vehicle loads,

$$Minimize\ Z = \sum_t \sum_h \sum_i \sum_j \sum_k \left[c_{hjk} l_{thjk} + \frac{r_h x_{thijk} p_i}{P_h} \right] \tag{10}$$

Where transportation cost c_{hjk} consists of fixed (f_h) and variable (v_h) costs,

$$c_{hjk} = f_h + s_{jk} v_h \tag{11}$$

Subject to

Non-negativity restriction on continuous variables,

$$x_{thijk} \geq 0, \quad x_{thijk} \in \mathrm{R} \quad \text{for all } t,h,i,j,k \tag{12}$$

Non-negativity and integer restrictions on integer variables,

$$l_{thjk} \geq 0, \quad l_{thjk} \in Z \quad \text{for all } t,h,j,k \tag{13}$$

The total commensurate vehicle capacity must at least equal the space required by all seedlings transported,

$$\sum_h l_{thjk} P_h \geq \sum_h \sum_i p_i x_{thijk} \quad \text{for all } t,j,k \tag{14}$$

The total number of seedlings delivered must equal the total seedling demand,

$$\sum_h \sum_j x_{thijk} = d_{tik} \quad \text{for all } t,i,k \tag{15}$$

The total number of seedlings delivered must not exceed the total number of seedlings produced,

$$\sum_t \sum_h \sum_k x_{thijk} \leq S_{ij} \quad \text{for all } i,j \tag{16}$$

In the context of testing the applicability of the models, they are both solved with and without the rule of home-territory. When this rule is applied, customer k is assigned to nursery unit j if the distance s_{jk} between them is less than 100 km. In this situation all seedlings to customer k are supplied by nursery unit j. Mostly for reasons of computational heaviness, the production-capacity restriction (Eq. 16) is not included in the MIP experiments dealing with the effects of allocating transportation among time periods. Therefore, in these experiments, the nurseries are treated as uncapacitated units for which the production volume is determined by the total demand assigned to them in the optimal solution.

The third optimization model introduced is the CMIP model for multi-echelon, multi-product, multi-plant PDSDP. In this model, potential locations of nursery units as well as locations of frosty warehouses and customer outlets are considered to be fixed. The CMIP model, like the previous models, is static; all the decisions are made within a single period. The parameters and variables included in the CMIP model are denoted as follows:

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, $\{i_1^K, i_3^K, i_5^K, ..., i_7^K\}$

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

$$H_g^E \text{ refers to a set of } \textit{existing} \text{ greenhouses of greenhouse type } g, \left\{ \begin{array}{l} h_1^E, h_2^E, ..., h_9^E \mid H_1 \\ h_{10}^E, h_{11}^E \mid H_2 \\ h_{12}^E, h_{13}^E, ..., h_{53}^E \mid H_3 \\ h_{54}^E, h_{55}^E, ..., h_{59}^E \mid H_4 \\ h_{60}^E, h_{61}^E \mid H_5 \\ h_{62}^E, h_{63}^E \mid H_6 \end{array} \right.$$

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

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

Input parameters 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 production-distribution 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 aim of the model is 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 is formulated as follows:

Objective function (17)

Minimize $Z = [$

Production

$$\sum_j \left(F_j Q_j + \sum_g \sum_h V_{gh} P^E_{ghj} + \sum_g \sum_h \left(V_{gh} + F_{gh}\right) P^B_{ghj} + \sum_t S_{tj} \left(X_{ijtw} + X_{ijtk}\right) \right) + \qquad (17.1)$$

Warehousing

$$\sum_{w} F_w R_w + \tag{17.2}$$

Transportation

$$\sum_{i^W}\sum_{j}\sum_{t}\sum_{w} X_{ijtw} C_{ijtw} + \sum_{i^K}\sum_{j}\sum_{t}\sum_{k} X_{ijtk} C_{ijtk} + \sum_{i^W}\sum_{w}\sum_{k} X_{iwk} C_{iwk} \quad] \tag{17.3}$$

Subject to

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

$$\sum_{j}\sum_{t} X_{ijtk} = D_{ik} \qquad \text{for all } i^K \in I^K, t \in T \text{ and } k \in K \tag{18}$$

$$\sum_{w} X_{iwk} = D_{ik} \qquad \text{for all } i^W \in I^W \text{ and } k \in K \tag{19}$$

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

$$\sum_{i^W}\sum_{j}\sum_{t} X_{ijtw} p_i \le R_w M_w \qquad \text{for all } w \in W \tag{20}$$

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

$$\sum_{j}\sum_{t} X_{ijtw} = \sum_{k} X_{iwk} \qquad \text{for all } i^W \in I^W \text{ and } w \in W \tag{21}$$

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.

$$\sum_{i^K}\sum_{i^W}\sum_{t} \left(X_{ijtk} + X_{ijtw} \right) a_i \le M_g \left(\sum_{h} P^E_{ghj}\, b_j + \sum_{h} P^B_{ghj} \right) \quad \text{for all } j \in J, w \in W, k \in K \text{ and } g \in G \tag{22}$$

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.

$$\sum_{h} \left(P^E_{ghj} + P^B_{ghj} \right) - \alpha Q_j \le 0 \qquad \text{for all } g \in G \text{ and } j \in J \tag{23}$$

Labor costs are determined as concave PWL 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. 24), whereas the previous stage must be fully utilized and the later stages must not be allowed to produce anything (Eq. 25).

$$\sum_{i^K}\sum_{i^W}\left(X_{ijtk}+X_{ijtw}\right)\le\left(B_{tj}-B_{(t-1)j}\right)A_{tj}\qquad\text{for all } j\in J, t\in T, k\in K \text{ and } w\in W \tag{24}$$

$$\frac{\sum_{i^K}\sum_{i^W}\left(X_{ij(t-1)k}+X_{ij(t-1)w}\right)}{B_{(t-1)j}-B_{(t-2)j}}\ge A_{tj}\qquad\text{for all } j\in J, t\in T, k\in K \text{ and } w\in W \tag{25}$$

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

$$R_w=\left\{0,\ 1\right\}\qquad\text{for all } w\in W \tag{26}$$

$$A_{tj}=\left\{0,\ 1\right\}\qquad\text{for all } t\in T \text{ and } j\in J \tag{27}$$

$$P^B_{ghj}\in Z_+\qquad\text{for all } g\in G,\ h\in H^B_g \text{ and } j\in J \tag{28}$$

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

$$0\le P^E_{ghj}\le 1\qquad\text{for all } g\in G, h\in H^E_g \text{ and } j\in J \tag{29}$$

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

$$X_{ijtw}\ge 0\qquad\text{for all } i\in I^W, j\in J, t\in T \text{ and } w\in W \tag{30}$$

$$X_{ijtk}\ge 0\qquad\text{for all } i\in I^K, j\in J, t\in T \text{ and } k\in K \tag{31}$$

$$X_{iwk}\ge 0\qquad\text{for all } i\in I^W, w\in W \text{ and } k\in K \tag{32}$$

The goal of this optimization is to compute the optimal production-distribution network with an optimal production-distribution plan on different planning levels. The model was originally constructed from a strategic perspective. 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*.

The next step is tactical level planning. Here, the current nursery units remain unchanged. This is done by setting decision variables Q_j (for all *j*) and R_w (for all *w*) equal to 1. However, if it is reasonable from the standpoint of cost-efficiency, more greenhouses can be built to increase the actual capacities of the nursery units. At this stage, a new constraint is introduced to ensure that the total area available for greenhouses is not exceeded in any nursery unit (Eq. 33). The solution of this experiment is further referred to as *TACT*.

$$EKAP_j+\sum_h P^B_{ghj}\,M_g\le N_j\qquad\text{for all } j\in J \text{ and } g\in G \tag{33}$$

The model is then used for solving operative level problems. Here decision variables Q_j (for all *j*) and R_w (for all *w*) are again set equal to 1; but in addition, P^B_{ghj} (for all *g*, h^B and *j*) is set equal to 0. According to these settings, building new greenhouses or obtaining savings from closing nursery units is not allowed in the operative level solution. The solution of this experiment is further referred to as *OPER*.

The convex PWL function is used as a surrogate for the actual nonlinear stepwise function describing the costs of using existing greenhouses to keep the model solvable within a reasonable CPU time. To evaluate the effects of this linearization on optimal solutions, Eq. 29 was replaced by Eq. 34 in the operative and tactical level computations. The effects of this replacement are estimated by comparing these results with *OPER* and *TACT*.

$$P^E_{ghj} = \{0,\ 1\} \qquad \text{for all } g \in G, h \in H^E_g \text{ and } j \in J \tag{34}$$

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 an optimal solution. In addition to solving basic PDSDPs, sensitivity analyses of customer demand and transportation costs are included in strategic level experiments. To obtain *OPER*, *TACT* and *STRAT* comparable to the current situation, the actual production-distribution network (further referred to as *OPER(CUR)*) of the company was also solved with the model. While *OPER(CUR)* was solved, 98% of the production allocation among nursery units was pre-determined.

3 Computational results

3.1 Quantifying ES in seedling production: A case study of mechanized packing

The theoretical outputs of the line were 22 900, 15 300 and 12 100 seedlings per effective working hour (E_0) for seedling trays including 121, 81 and 64 seedlings per tray, respectively. Corresponding output values for work place time (W_0) were 19 300, 12 900 and 10 200 seedlings per hour (cycle time 19 seconds/tray, machine interruptions 4% and rest pauses 12% of W_0). Productivity figures for different types of seedling trays are presented in Fig. 5.

Reduction of the cycle time naturally increased productivity. The observed cycle time was 19 seconds/tray. The theoretical packing-disinfection unit costs were calculated for all types of seedling trays used in the nursery unit (Plantek 64F, 81F and 121F), but only Plantek 81F was actually studied. The impact of output dimension of scale on unit costs of packing was included in the analysis in terms of different annual packing volumes. Manual packing costs were calculated based on the practical experiences of nursery managers. The comparable manual packing-disinfection unit cost was 0.011 € per seedling, derived from the average output of 1500 seedlings (Plantek 81F) per worker in a work place hour (W_0). Material costs, such those for seedling trays and cardboard boxes, are not included in the cost functions presented in Fig. 6.

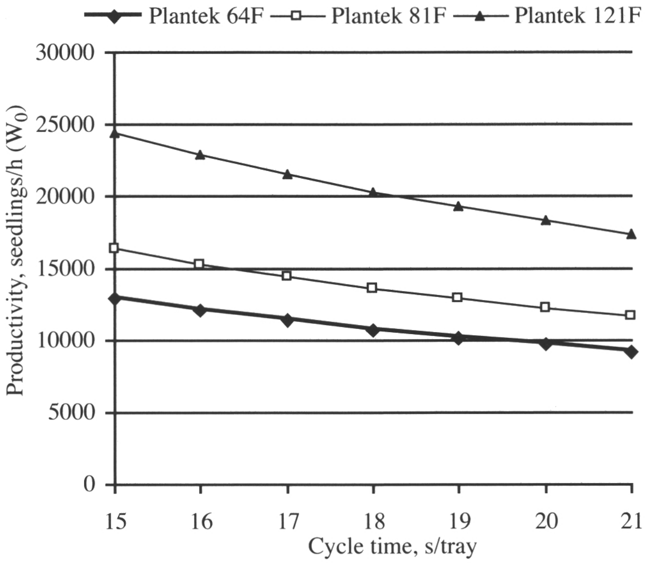

Fig. 5. Productivity of the packing-disinfection line in terms of the number of seedlings packed, presented as a function of cycle time.

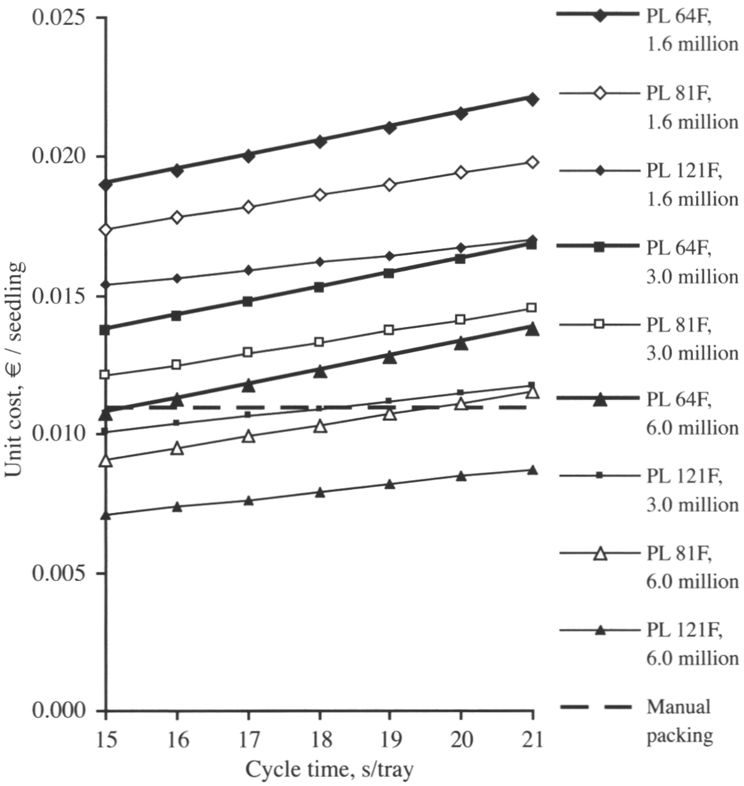

Fig. 6. Impacts of the annual number of seedlings processed in packing-disinfection line and the cycle time of the line on packing unit costs of seedlings grown in Plantek 64F (PL64F), 81F (PL81F) and 121F (PL121F) seedling trays. Costs of manual packing of seedlings and disinfection of seedling trays are represented by a dashed line.

Increasing the annual packing volume up to 3.0 million seedlings from the 1.6 million seedlings of the study season would reduce packing-disinfecting unit costs by 25–32% depending on the seedling types packed. Furthermore, if the annual number of packed seedlings increased to 6.0 million, the savings would be 39–51% of the present unit costs. While the total cost/output data were fitted to Eq. 1 (see chapter 2.1), the values for parameters *a* and *b* were estimated to be 8.8 and 0.57, respectively. Compared to manual packing of seedlings (PL81F) and disinfection of seedling trays, the mechanized packing-disinfection line with observed cycle time (19 seconds/tray) is not cost-efficient until the annual packing volume exceeds 6.1 million seedlings (Table 2; depreciation period 15 years, interest requirement 6%). The slight difference between the values presented in Fig. 6 and Table 2 is caused by the longer depreciation period (30 years) used in Fig. 2 for calculating the costs of the building where the packing-disinfection line was located.

Table 2. Break-even points for annual packing volume (PL81F, cycle time 19 seconds/tray) with different interest requirements and durations of the depreciation period beyond which mechanized packing of seedlings and disinfection of seedling trays is cheaper than corresponding manual operations.

	Depreciation period, yrs		
Interest requirement,%	5	10	15
3	12520000	6860000	4970000
6	13680000	8010000	6120000
9	14830000	9160000	7270000
12	15980000	10310000	8430000

Figures represent annual packing volumes [seedlings/year].

Table 3. Investment sums equivalent to the annual costs of manual counting of seedlings in the packing-disinfection line with different economic interest requirements and durations of the depreciation period.

	Depreciation period, yrs		
Interest requirement,%	5	10	15
3	14800	27200	37900
6	13600	23600	31200
9	12600	20800	26500
12	11800	18600	23000

Figures represent investment sums [€].

Examined from the more technical standpoint, for successful use of the packing line, all six workers were needed; and the idle times were not significant. With the exception of one worker, whose only essential task was to count the unsuitable seedlings (97% of E_0), the workers had many parallel tasks to do. The proportion of usable seedlings in the trays varied between 80% and 99%. As the deviation is so high, to guarantee a good-quality product, it is necessary to count seedlings and fill the seedling packages to the given number of seedlings. Seedlings could also be counted mechanically, in which case a mechanized counter would compensate for one worker. In the present study with an annual packing volume of 3 million seedlings, that would lead to savings of ca. 2900 € per year (wage and social expenses ca. 12.6 €/h, working time ca. 230 h/a, PL81F). Equivalent investment sums with salvage value of 10% for different economic interest requirements and durations of the depreciation period are presented in Table 3.

3.2 Effects of production strategy and transportation planning method on transportation costs

Results of the cost accounting used as input data for optimization models showed that a truck with a trailer was the most cost-efficient vehicle for transporting seedlings more than 16 km, when the assumptions of full vehicle loads and all-year usage of the vehicles were valid. For shorter distances, the most cost-efficient vehicle was a pickup truck (Fig. 7).

To analyze the effects of different seedling production and long-distance transportation strategies on transportation costs, twelve experiments (DTS/CTS x S1...S6, see Figs. 8 and 9) were carried out. The current production strategy (S2) with five nursery units using DTS was set as the reference value (100) for the comparisons. Due to an increase in the total transportation distance, a decrease in the number of nursery units raised the total transportation cost. The increase in cost was much smaller when CTS was applied to transportation planning instead of DTS. In general, depending on the production strategy used, applying CTS decreased transportation costs from 13.0% to 36.5% (Fig. 8). The advantages of CTS compared to DTS were greatest when all production was centralized to one nursery unit. It should be noted that a decrease in the number of nursery units meant only putting an end to production, so that the original five units continued as sales and storage sites. In DTS, due to unbalanced production-demand ratio of single nursery units, internal transportation between the nursery units of the company is needed.

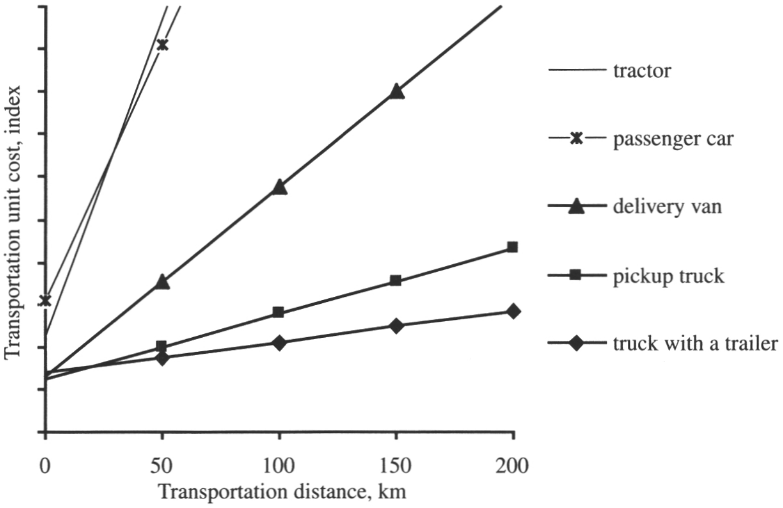

Fig. 7. Cost curves including terminal, fixed and variable costs for different seedling transportation vehicles with the assumptions of full loads and all-year usage of the vehicles.

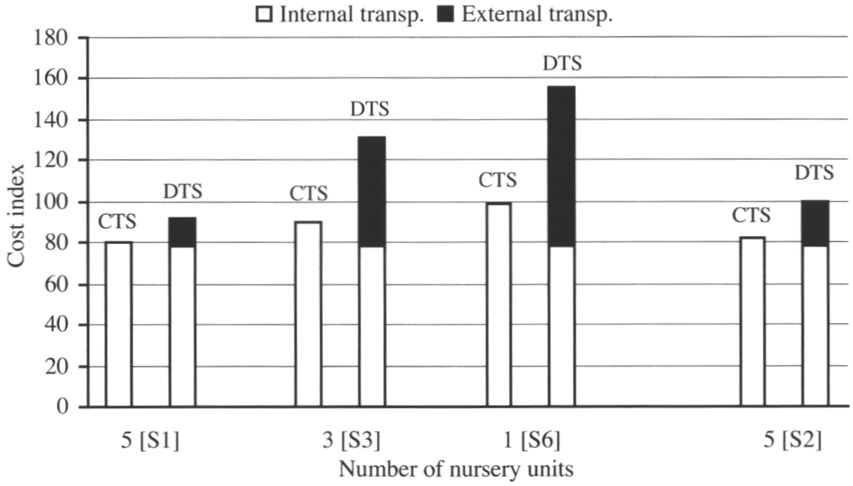

Fig. 8. Effect of number of production units [production strategy number in brackets] and transportation planning method (CTS/DTS) on transportation costs of the nursery company.

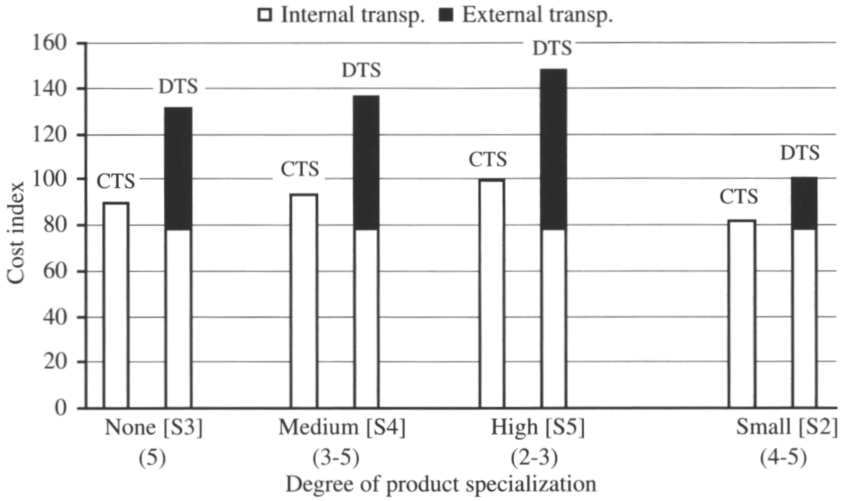

Fig. 9. Effects of product specialization [production strategy number in brackets] and transportation planning method (CTS/DTS) on transportation costs of the nursery company.

In order to determine the effects of product specialization on transportation costs, the production strategy of three nursery units was selected for closer analysis. To determine these effects, three different production strategies (S3, S4 and S5) for allocation of production of different seedling types among nursery units were studied. The same comparison as above was made between CTS and DTS. The current production strategy (S2) was again used as a point of comparison with a reference value of 100 (Fig. 9).

As expected, the increase in degree of product specialization among nursery units increased transportation costs. The difference between no product specialization and high degree of specialization in transportation costs was 10.1% when CTS was used and 13.2% when DTS was applied. Thus, the increase in specialization slightly emphasized the advantages of CTS.

The MIP model was used to quantify the effect of linearization on the accuracy of the LP model results in the business situation of three identical nursery units (S3). First, optimal seedling shipments were picked up from the solution of the LP model and set into the MIP model as delivery restrictions; thus the seedling shipments delivered were the same in both models, and the solutions could be compared merely from the standpoint of authenticity of transportation costs. The only optimization carried out at this stage with the MIP model was the allocation of seedling shipments between different vehicle types. As a consequence of linearization, total transportation costs calculated with the LP model, further used as an index value of 100, were 4.1% (4.7% when the rule of home-territories was included) smaller than the corresponding costs of the MIP model (Table 4).

The home-territory restriction reduced computing time considerably. For instance, optimization of seedling transportation in S3 with the MIP model took 10 h 41 min and 5 sec without the home-territory restriction and 7 h 58 min and 25 sec when home-territories were included. Due to their computational heaviness, each of the MIP model experiments was split into several parts. The experiments were split by dividing customers into smaller groups and solving the transportation of one group at a time. Thus, restrictions on the production capacities of nursery units could not be controlled during computation of the MIP model; and after the experiments presented above, these restrictions were excluded from the transportation models.

Next, seedling transportation was optimized in S1, S3 and S6 with the LP and MIP models; and the solutions were compared to each other. These experiments were done with the home-territory restriction but without the restriction on production capacities of nursery units. The main result of this comparison was that differences in allocation of orders among nursery units occurred only in the

Table 4. Effect of linearization on transportation costs in the LP model solution compared to those calculated with the MIP model with and without the home-territory restriction.

Nursery unit *j*	1	2	3	Total	
LP model	37.2	35.2	27.6	100.0	Index
MIP model	38.4	36.7	29.3	104.3	Index
Total cost difference	–3.2	–3.9	–5.5	–4.1	%
LP (home-territories included)	35.0	35.6	30.9	101.6	Index
MIP (home-territories included)	36.2	37.1	33.3	106.6	Index
Total cost difference	–3.2	–4.0	–7.2	–4.7	%

Table 5. Effect of number of seedlings included in the optimization on accuracy of the optimal transportation costs in the LP model solution.

No. of transported seedlings	LP cost index*	MIP cost index*	LP compared to MIP,%
23 850 000	95.1	98.1	–3.0
12 640 500	49.8	53.5	–7.0
7 393 500	30.4	34.9	–12.9
3 816 000	14.9	19.7	–24.4

* Index scale is the same as in Table 4.

case of the current five nursery units (S1). In the production strategies (S3 and S6) of fewer nursery units, the optimal solution was exactly the same in both models. The differences in transportation costs between the solutions of the LP and MIP models were 2.7–3.9%, depending on the number of nursery units; the difference decreased slightly when the number of nursery units increased.

Weakening of the accuracy of LP model solutions due to inclusion of a smaller number of seedlings in the optimization was studied by comparing these solutions to the corresponding solutions of the MIP model. These experiments were again carried out in the S3. As can be seen in Table 5, the computational accuracy of the LP model clearly deteriorated due to the effects of linearization, while the number of seedlings included in optimization decreased. This was caused by a decrease in average number of seedlings transported to each customer, which led to a greater proportion of seedlings transported in LTL shipments. The numbers of seedlings included in the optimizations, presented in Table 5, are examples from the experiments related to studying how allocating transportation among time periods affects transportation costs.

To explore how dividing transportation into 1–5 time periods affects transportation costs, seven experiments were done with the MIP model in the S1, S3 and S6. Due to the computational heaviness of the MIP model, the five-period model was solved only in the case of S3. In addition to total transportation costs, the solutions included optimal allocation of transportation between a truck with a trailer and a pickup truck (Table 6).

Transportation costs rose as the number of seedlings transported per route decreased due to the increase in number of transportation periods. Compared to the one-period model, the three-period model raised transportation costs by 9.2–11.8%, depending on the number of nursery units. The increase was slightly smaller in situations where the number of nursery units was larger. Correspondingly, the total transportation costs of the five-period model, which was applied only to the S3, were 19.3% higher than the costs of the one-period model. Here, the increase in costs was again caused by the greater proportion of seedlings transported in LTL shipments and by pickup truck instead of a truck with a trailer.

Table 6. Effects of the numbers of nursery units and transportation periods on transportation costs of the nursery company and the optimal allocation of transportation between a truck with a trailer and a pickup truck. Comparison values are denoted by –.

Production strategy	No. of nursery units	No. of transportation periods	Cost difference, %	Cost index*	Transported by truck with a trailer,%	Transported by pickup truck,%
S6	1	1	–	114.6	96.0	4.0
	1	3	11.8	128.1	87.0	13.0
S3	3	1	–	98.1	95.7	4.3
	3	3	10.3	108.2	84.1	15.9
	3	5	19.3	117.0	77.0	23.0
S1	5	1	–	89.4	94.1	5.9
	5	3	9.2	97.6	78.4	21.6

* Index scale is the same as in Tables 4 and 5.

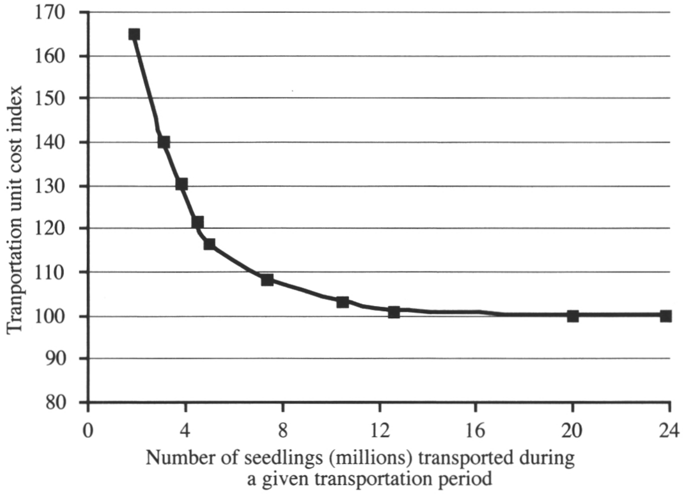

Fig. 10. Effect of number of seedlings transported within a transportation period on transportation unit costs. The observations are based on the numbers of seedlings transported within different time periods in the one-period, three-period and five-period models.

When the number of nursery units rose, the proportion of seedlings transported by pickup truck increased slightly. This increase was, however, more marked when the number of transportation periods increased. In general, the smaller the number of seedlings transported, the higher were the costs and the larger was the proportion of seedlings transported by pickup truck. The effect of the number of seedlings transported within a time period on the periodical transportation unit costs is illustrated in Fig.10.

As can be seen in Fig. 10, when the number of seedlings transported during a certain period decreased, transportation unit costs increased exponentially. With the material used, the increase in transportation unit costs seems to be very slight until the number of transported seedlings decreases to less than 12 000 000; from then on, the increase in costs is strongly accelerated. The increase in costs is derived from the accelerated increase in the proportion of seedlings transported in LTL shipments and by pickup truck instead of by a truck with a trailer while the total number of seedlings decreases from 12 000 000.

3.3 Optimization of the production-distribution network

In this paragraph, the CMIP model solutions (*OPER(CUR)*, *OPER*, *TACT* and *STRAT*) are used to analyze different production-distribution networks of the nursery company studied. As mentioned, the PWL function was used as a surrogate for an actual nonlinear stepwise function describing the costs of using existing greenhouses. The effects of this linearization were estimated by solving operative 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. In strategic level computations the difference would probably be even smaller. Therefore, the accuracy of the model solutions presented below has not deteriorated markedly due to the linearization.

In general, the results showed that ES could be exploited much more than the company does today in *OPER(CUR)*. At the first stage, the CMIP model was solved with applicable constraints for each planning level. In *OPER* and *TACT* the number of nursery units was constrained to equal five. As a result, all nursery units were opened, but production was allocated only among three (*OPER*) or between two (*TACT*) units. In *OPER*, where building of new greenhouses was not allowed, this indicates the existence of inefficient over-capacity of greenhouse area. In Table 7, the fixed costs of the nursery units to which no production was allocated are omitted from the indexes. 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 five frosty warehouses, the number of opened frosty warehouses varied between four and five. A certain frosty warehouse was opened only in *OPER(CUR)*, in which its opening was pre-determined, and in *STRAT*.

When other production-distribution network designs were applied, the cost savings varied from 11.3% to 21.3% compared to *OPER(CUR)* (Table 7). Moving from operative- 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 were built in nursery unit 1.

Table 7. Main features, total cost indexes and allocation of costs between transportation and production in optimal production-distribution networks on different planning levels. The total cost index for *OPER(CUR)* is 100.

Planning level	Abbr. of the solution	No. of nursery units opened	No. of frosty warehouses opened	No. of new greenhouses built	Total cost index*	Transportation costs,%	Production costs
Current	*OPER(CUR)*	5	5	Not allowed	100.0	4.6	95.4
Operative	*OPER*	3	4	Not allowed	88.7	6.1	93.9
Tactical	*TACT*	2	4	2	83.9	6.6	93.4
Strategic	*STRAT*	1	5	10	78.7	8.6	91.4

* Index scale is not comparable to previous indexes.

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 the number of new greenhouses built in nursery unit 1, which produced all seedlings. The variations were 25 and 50 percent increases and a 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 rose more than four-fold.

Nursery labor costs made up 82.7–89.5% of the total production costs in the production-distribution network. Compared to *OPER(CUR)*, labor costs per seedling were 11.8, 17.4 and 29.6 percent smaller in *OPER*, *TACT* and *STRAT*, respectively. In general, the greater the number of seedlings produced in the nursery unit, the smaller was the labor cost per seedling (Table 8). 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)*.

All computations presented in chapters 3.2 and 3.3 were performed with the What's Best! Industrial optimization solver on a PC with 256 MB RAM and a Pentium III processor running under Windows 2000 operating system. CPU times for finding *OPER(CUR)*, *OPER*, *TACT* and *STRAT* were 38, 85, 51 and 71 seconds, respectively. While the use of existing greenhouses was determined according to Eq. 33, the CPU times for operative and tactical level problems were several hours.

Table 8. Nursery unit-specific information in different production-distribution network solutions (*OPER(CUR), OPER, TACT, STRAT*).

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

* Index scale is not comparable to previous indexes.

4 Discussion

4.1 Contribution and synthesis of the results

The secondary research questions (SQs) were initially posed in order to support the primary research question (PQ). Thus, the answer to the PQ is formed as a summary of the answers to the SQs. In this chapter, the SQs are not enumerated but are addressed from the managerial standpoint, closing with general conclusions about possibilities to improve cost-efficiency in the PDSs of the forest nursery industry. Finally, possible pitfalls of the approach and future scenarios of Finnish nursery industry are discussed briefly.

The cost comparisons related to the mechanized packing-disinfection line showed that most of the nursery units in Finland are still too small to gain a real advantage from large-scale production, at least from the standpoint of such individual investment in mechanization. However, as all the requirements presented for profitable mechanization (Harstela 2000), and in particular, sufficient annual packing volume, i.e. 6.1 million PL81F seedlings at the minimum when the interest requirement of 6% and a depreciation period of 15 years were used, come true, the packing-disinfection line seems to be a cost-efficient alternative to manual operation. Sensitivity analysis of the interest requirement showed that a 3% increase in the interest requirement would raise the annual packing volume needed for profitable mechanization by approximately 1.15 million seedlings. On the other hand, technical development can make mechanization more advantageous in the future. The company which provided the packing machine studied, for instance, reports that the cycle time of the machine has decreased from 19 to 12 seconds (www.lannenplantsystems.com). In theory, when all other factors affecting productivity and costs of the machine are assumed unchanged, this reduction would mean 46% decrease in the number of seedlings packed per year required to profitable mechanization.

As a result from estimation of the relationship between the cost and capacity for different industrial investments, Haldi & Whitcomb (1967) presented a summary distribution of the values of scale coefficient *b* (see chapter 2.1). In that distribution, the mode class was 0.50–0.59. The packing-disinfection line also fell into this class, implying clearly increasing returns to scale within the output range (1.6–6.0 million seedlings/year) included in the analyses. Nevertheless, it should be noted that for estimating possible DS, such as maintenance of the line or increasing need for two- or three-shift work while the scale increases, the material was limited. The need for shift-work should not, however, be reached with current production technology until the annual packing volume exceeds about 6.5 million seedlings.

The relatively high, and in many cases unattained, level of production volume required for economically reasonable mechanization seems to be one reason for the success of small-scale and by-business nurseries in the Finnish nursery industry today as Petäjistö and Mäkinen (1999) also pondered. Some nursery managers have said that the critical point for cost-efficient mechanization of certain nursery production stages is an annual production of ca. 10 million seedlings. Taking into account the fact that not all seedlings are packed, this estimation seems to be reasonable for mechanizing the packing of seedlings.

Achieving ES in production by centralizing production to larger production units leads to an increase in outbound transportation costs. Nevertheless, the increase would be much smaller if CTS was applied instead of the current DTS; a decrease in the number of nursery units from the current five (S2) to three (S4), for instance, increased the total transportation costs by only 13.5% when CTS was used in planning transportation and by 35.6% when DTS was applied. It can be concluded, as also Beckenstein (1975) did, that product specialization, i.e. shifting to more unbalanced production strategy, did not increase transportation costs as much as centralizing production by decreasing the number of production units. Naturally, evaluation of the optimal production-distribution strategies is much more complex than merely accounting and optimizing transportation costs. First, the savings in costs achieved by a more efficient system for managing transportation should be compared to the costs of acquiring, maintaining and using the system. Nevertheless, the most crucial comparison would be the one between increased transportation costs caused by longer transportation distances with a smaller number of nursery units and economic advantages achieved by larger production units.

The results of Articles II and III are encouraging for the transportation of seedlings by a truck with a trailer. Nevertheless, especially when rather short distances were at issue, the transportation costs of a truck with a trailer and a pickup truck were quite similar; and for both of them the sum of the terminal and the fixed costs was crucial (see Fig. 7). Thus, from the standpoint of the stability of the results, the order of these two vehicles might be sensitive to changes in initial cost accounting data. The assumption of all-year usage of the vehicles was based on the idea of externalized transportation activities. McKinnon (1989), Lakhal et al. (2001) and also the managers of the company stated that physical distribution is, when seen as non-strategic, an activity that producers purchase from outside agencies rather than organize themselves. This view is emphasized in seedling transportation due to seasonal operation periods and the need for special equipment.

In Finland, the total logistics costs account, on average, for ca. 10% of a company's turnover; and transportation makes up ca. 40% of the total logistics costs (Kanerva et al. 1997). In this research, depending on the production and transportation strategies applied, operative long-distance transportation costs varied between 1.6–3.1% of the company's turnover. However, only direct costs were included in these figures; and thus, the profit margin of a third-party transportation company and costs of managing transportation, for instance, were ignored. In these analyses (Article II), transportation costs were treated as linear.

Therefore, a general empirical observation that transport rates normally taper with increasing transport distance, known as economies of distance (McCann 2001), wasn't either taken into account. On the other hand, the effects of ES in transportation on load- and route-specific unit costs were examined in Article III. It should also be noted that only a part of the whole distribution chain was included in the analyses (see Fig. 2).

The applicability of the LP model, compared to that of the MIP model, to allocation of orders among nursery units improved when the number of nursery units decreased. In the production strategy of five nursery units, which is the current strategy of the company studied, there were some differences in allocation of orders between two of the five nursery units, whereas the other parts of the optimal solutions were the same. Altogether, these differences were not very great. In the production strategies of three or less nursery units, the minimum cost solutions of the models compared were exactly the same. Therefore, it seems that the current geographical density of the Finnish nursery units owned by the same company is close to the limit from which (for more scattered nursery units) no additional value can be reached by applying MIP to management of seedling transportation instead of LP. As a point 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. Taking into account the fact that development seems to be going towards larger and more scattered nursery units; LP seems to be the most workable method for management of seedling transportation. However, the stability of this result greatly depends on the geographical density of nursery units owned by the same company.

As a summary of Articles II–III, transportation of seedlings was, on the one hand, modeled in more detail compared to the previous models introduced in this field. From this standpoint, the approach was more oriented toward the operative level than those presented by Grevatt & Wardle (1967) and Laakkonen (1979). To enhance operative level knowledge of seedling transportation, the effects of transportation mode used and capacity requirements of different seedling types were studied as well as the linearization done in LP formulation. On the other hand, examined from a more strategic perspective, much attention was paid to quantifying the effects of different decisions related to the production strategy, i.e. to number of production units, degree of product specialization among them and number of distribution periods, on total transportation costs of the company. In addition, new information was obtained about the applicability of different OR techniques to the management of seedling transportation.

The CMIP model introduced (Article IV) was the first attempt to solve PDSDP in the forest nursery industry. The CMIP 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 production-distribution network in the long-run. The operative 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 ES 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 rationality of the centralization strategy. 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 CMIP model 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 ES achieved in labor costs are crucial in the CMIP model results. While other labor intensive branches of industry have been studied, opposite results to those of this research concerning labor costs in production centralization/decentralization dilemma have also been obtained (e.g. Mariotti 1984, Crandall 1996). The difference between the results is mainly caused by the fact that in the Finnish nursery industry, labor unit costs were observed to decrease while the plant-specific scale increased, whereas Mariotti (1984) and Crandall (1996) 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 & 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. When it comes to the stability of the results, it should be kept in mind that labor costs were 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 ES 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.

To summarize the results obtained, there are possibilities to achieve greater ES in Finnish nursery industry by centralizing seedling production. The main aspects supporting this development direction are better premises for cost-efficient mechanization of production stages (Article I) and a chance for more efficient use of labor and general facilities needed in seedling production (Article IV). Transportation costs are not an obstacle for centralization, especially when OR techniques are used in transportation planning (Articles II–III).

4.2 Assessment of the research

4.2.1 Relevance

The topic of this research is relevant for many reasons. First, the unit cost trend in the silvicultural operations, including planting, has been upwards; whereas since the 1980's the corresponding cost trend in wood procurement, for instance, has been downwards (Finnish statistical... 2003). Secondly, the nursery industry in Finland has undergone huge changes during the 1990's; large-scale nursery companies were hived off from the state so that either the production volumes of the companies or the pricing of seedlings were not anymore at the hands of the state; and annual seedling demand decreased drastically. Third, technical development has opened new possibilities, such as more sophisticated production machines, for producing seedlings and for managing supply chain activities such as production and distribution. Fourth, from the perspective of the company studied, because of increasing domestic and international competition, it would be hard even to preserve the current market share without developing the cost-efficiency of the PDS. Altogether, there obviously was a need for information about the effects of different managerial decisions on costs of the PDS. In addition, there was a lack of applicable decision support tools for management of the PDS in forest nursery industry.

Some evidence of the relevancy of the research, in terms of managerial implications occurred as changes in the production strategy of the company studied, was observed during the research process. The company has, for instance, managed to increase the annual packing volume over the critical point of cost-efficient mechanized packing by centralizing production of certain seedling types to the nursery unit where the mechanized packing-disinfection line is located. The mode of operation, in a broad sense, on which the research was based, i.e. nursery companies transporting seedlings to intermediate storage areas from which ahead the delivery of seedlings to regeneration areas is organized by FOAs, seems to be successfully implemented by some nursery companies and FOAs (Rantala 2003).

As it has an important effect on achieving ES in seedling production, the number of nursery units is under examination in many phases of the research. The relevance of this approach might be debatable, because a nursery unit may have some positive effects on the overall success of a nursery company despite the increase it causes in average production costs. However, despite the privatization in the 1990's, the ownership of the Finnish nursery industry is still state-based. In this situation, examination of the number of nursery units from the standpoint of cost-efficiency appears to be relevant. In this context, it can also be mentioned that during the research work, the Finnish Ministry of Agriculture and Forestry has announced that a working group will be established for planning the rationalization of the Finnish nursery industry.

4.2.2 Validity and reliability

Two basic types of assessments of measurement quality need to be done before the researcher can claim that the measurement process is sufficiently valid (Dröge 1996). The first is reliability, which is a question of whether it is likely that consistent results are obtained regardless of who carries out the research process. For measurement to be valid, reliability is necessary but not sufficient. The second assessment is validity, which is epitomized by the questions: "Are we measuring what we think we are measuring?" (e.g. Kerlinger 1973) or in OR "How well does a model represent the real world system under study?" (e.g. Asikainen 1995). Thus, validity assessment involves demonstrating that the theoretical construct measured by indicators is actually being measured by those indicators (Dröge 1996 and 1997). In general, perfect reliability and/or validity cannot be achieved; rather, the goal should be to achieve sufficient reliability and validity for the particular purpose of the researcher (Dröge 1996).

The mechanized packing-disinfection line studied (Article I) was a prototype working for the first year. Because the work rate of the production line was machine-controlled, the material investigated here may be large enough to estimate the productivity and to analyze the tasks of the workers. Thus, the data on effective working time (E_0) can be considered reliable. For estimating the machine interruptions, however, the material is very limited. The higher operation speed options studied may increase the risk of interruptions, but the material used here was insufficient for estimating that effect. Nor could workers' ability to manage their tasks faster be observed in practice. Thus the estimations of cost savings due to decreasing the cycle time may be optimistic.

In Articles II–IV, the reliability relies mainly on two points; firstly, the objectively gathered information about the attributes selected for measurement, and secondly, the accurate programming of the optimization models. The latter is actually a question of model verification. In Article IV, in particular, the researcher could not influence the material used as input data for optimization experiments; the data sources used were the company's accounting information, investment calculations with depreciation plans and the customer database. Nevertheless, the cost factors and facilities included in the CMIP model were naturally chosen by the researcher but based on interviews of nursery managers.

In general terms, verification means that a model is scrutinized to ascertain whether any technical mistakes have been made in model construction. For that purpose, some model solutions were tested, for instance, by ascertaining that the observed solutions could not be improved manually and checking that only feasible solutions were accepted. In addition, sensitivity analyses with different input parameters were made to see that the model response is in line with what was expected. Finally, the observed results were evaluated by comparing them to the opinions of nursery managers and researchers.

From the standpoint of validity in optimization experiments, the relative differences between the values of different factors included in the models are all that the researcher needs to be concerned with; it is often not essential whether the model response and the actual system values are identical. Here, while empirical validation of the optimization models was lacking, the validity of the research was tested from the standpoint of the logicalness of the model outputs. The results of sensitivity analysis were logical and supported the views, obtained earlier e.g. by Mikkonen (1983), that when practical level problems are at issue, the changes in model output values are usually rather small near the optimal solution.

Validity of the research can also be evaluated by comparing the results to those obtained in earlier studies. There is little literature, at least in the field of forest technology, about quantifying the effect of optimization on the total costs of production-distribution link. However, for the sake of comparison, Williamson & Nieuwenhuis (1995) reported 38% and Bergdahl et al. (2003) 8–9% reductions in transport output to be possible by applying to planning of timber transportation an approach similar to that used here for planning of seedling transportation. The results obtained in this research seem to lie between those observations. In comparison to earlier optimization-based studies for greenhouse production, 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.

The greatest weakness of this research (Articles II–IV) is the lack of empirical validation of the optimization models. Nevertheless, this is a typical weakness in studies on applying OR approach to decision-making in forest operations. Steiguer et al. (2003), for instance, presented an annotated list of references to numerous studies in this area; and only about half of the citations referred to empirical tests. In this research, the reason for the lack of empirical tests is simple: the company studied, like most other large-scale Finnish nursery companies, was during the research process just beginning to plan how to rationalize their supply chain activities. Thus, there was a set of minor problems to solve before the models could be validated empirically, not to mention the managerial implication of the optimization approach. For that reason, in the context of optimization of production and distribution activities (Articles II–IV), it might be more realistic at this stage to talk about theoretical possibilities for rationalization by applying the OR techniques introduced. Two assumptions, used in Articles II–IV, should, in particular, be taken into account when the models are 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.

The material for each study (Articles I–IV) covered only a time-period of one year. So the materials used do not create a very firm basis for longitudinal analyses. Nevertheless, in the Finnish nursery industry, the most important cost factors of seedling production as well as the spatial information about the nursery units and customers of nursery companies have thus far been quite static. Geographical and organizational differences were avoided by studying the same company throughout the research process, which on the other hand, raises a question about the generalization of the research. In summary, the results have the level of reliability that satisfies the researcher. Despite the deficiencies in empirical testing of the models, the researcher is confident about their applicability to describe the essential activities of PDS in the nursery industry.

4.2.3 Possibilities and limitations of generalization

Generalizability is a major concern to those who do, and use, research (Lee & Baskerville 2003). According to Holt & Turner (1970), "the goal of any science is to develop a valid, precise and verified general theory". In its general meaning, generalizability is the ability to construct a general theory by applying findings about a sample to a population. The information obtained from any measurement procedure is to some degree fallible (Brennan 2001). The choice of a specific method for measurement, for instance, involves a restriction on the set of conditions for which the generalization is intended. In the next paragraph, the generalizability of the research is considered from the standpoint of conditions in which the research was carried out.

The research was carried out in the operational environment of a Finnish nursery company. However, 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 the cost-efficiency of PDSs, 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. The material was collected in the years 2000–2003. So it should be noted that during these years, the company studied, like most other nursery companies in Finland, was just getting used to the changes that had occurred in the nursery industry during the 1990's.

In this research, the premises for cost-efficient mechanization in the Finnish nursery industry were evaluated only on the level of individual production stage (Article I). Although the packing-disinfection line studied is a typical investment in mechanization of the seedling production process, one has to be careful when these results are generalized to other production stages in the nursery industry. The transportation models introduced and the results obtained in Articles II & III might be suitable for analogous freight transportation problems in other branches of industry. Actually, there were no special features in these models which would restrict their use only to management of seedling transportation. The CMIP model introduced in Article IV could also be modified rather easily to respond to the needs of other labor-intensive branches of industry dealing with analogous PDSDPs. Nevertheless, outside the environment and material used in analyses some results might be irrelevant.

4.3 Outlook for the future

In the future, characteristics of post-industrialism, such as international competition, probably will become more common also in the nursery business. Thus, it is presumable that seedling markets in the Nordic and Baltic Sea region will merge into one. Consequently, the adaptability and competitiveness of the nursery companies will be increasingly emphasized. International markets are more often seen as a threat than a possibility for Finnish nursery companies. This is a consequence of the fact that most of the companies are not thus far used to operating in the most cost-efficient manner. In addition, marketing acts of the companies have mostly been directed to customers located near the nursery units. Altogether, it seems that so far the companies have not been willing to extend their marketing areas despite the well-known fact that in this type of market situation, the company with the greatest share of the market is also the most cost-efficient producer. In the current situation, the greatest threat for Finnish companies appears to be a decrease in proportion of the domestic demand assigned to them. So far, the seedlings imported to Finnish markets have come mainly from Sweden, where the availability and price of different production factors are somewhat similar to the Finnish circumstances. In the future, taking into account the labor-intensiveness of the nursery industry and considerably cheap costs of well-managed seedling distribution, an increase in import of seedlings from low-paid countries near Finnish markets is also possible. At least these countries seem to be an attractive alternative for placing seedling production.

In any case, taking into account the dominant role of ES in seedling production, an important factor enabling cost-efficient seedling production is the volume of seedling demand. In addition to the success in international competition, the demand assigned to Finnish nursery companies depends, on the one hand, on the annual amount of clear-cuttings, which in turn is greatly affected by general economic trends (e.g. Hänninen 2003) and on the other hand, on the struggle between natural regeneration and forest cultivation. As far as the struggle between natural and artificial regeneration is concerned, improved cost-efficiency of the PDSs in the nursery industry makes possible lower prices for seedlings, which in turn improves economic profitability of artificial regeneration.

In Finland, taking into account success factors such as flexibility, special services and localness of small-scale and by-business nurseries (Petäjistö & Mäkinen 1999), it seems that the nursery industry will in the future become more and more polarized: large-scale units producing high-volume products such as the most popular container seedling types, and small-scale producers supplying differentiated lower-demand seedling types and special service packages to local markets. The same development appears to be underway in Sweden, where diversity in the scale of nursery units is already much clearer than in Finland. Hodges & Haydu (2000) reported an analogous example of the same kind of development in the ornamental plant nursery industry in United

States. In any case, the cost-efficiency of the PDS will be an important factor distinguishing successful nursery companies from others, especially among large-scale producers.

4.4 Needs for further research

The mode of operation, into which frames the research was placed, assumed that the seedlings included in the experiments were shipped to FOAs' intermediate storage areas, which were considered to be customers and final demand points of the nursery company. Nevertheless, transportation from intermediate storage areas to regeneration areas is also needed. In practice, the interface between the long-distance transportation to intermediate storage areas and the transportation to regeneration areas is in some cases rather indefinite. Usually when seedlings are transported to regeneration areas, the unit size of each consignment is smaller than that used in Articles II–IV. Thus, to deliver the seedlings to regeneration areas as cost-efficiently as possible, the convenience of each vehicle type and OR technique used in transportation optimization should be re-evaluated. Neither the LP model nor the MIP model took into account the routing possibilities of customer locations. Nevertheless, the numbers of seedlings transported between nursery units and intermediate storage places are rarely smaller than a vehicle load, and intermediate storage places are often so far from each other that routing might not be more cost-efficient than single transportation to each customer. In any case, in the context of optimal delivery to regeneration areas, the applicability of vehicle-routing algorithms (see e.g. Lukka 1987, Ballou 2004) also needs to be studied.

The optimization models need to be validated empirically. In addition, to obtain more information about core issues and problems in operations management, an empirical research design is often recommended, in addition to modeling-based research, for improving the content validity of the research (Rungtusanatham 1998). As the labor costs were of great significance in results of integrated production-distribution optimization, shadow price and sensitivity analysis (see e.g. Hillier & Lieberman 1974) concerning e.g. the effects of changes in the boundaries of production stages as a consequence of increased level of mechanization, might provide useful additional information for interpretation of the results. Although production planning at the level of single nursery units remained outside this research, added value might be achieved by combining the CMIP model with the production planning model presented by Laakkonen (1978). Furthermore, constructing a model for prediction of annual seedling demand in a certain market area might help companies in production planning and also in implementation of the models introduced in this paper. A marketing research approach would probably also bring valuable decision-support information about the characteristics related to seedling demand.

Analyses of the internal logistics of single nursery units would provide important information needed in re-engineering production processes in current nursery units, and especially while production is being centralized to larger nursery units. In addition, studying both vertical and horizontal networking and partnership issues might equip the nursery industry to improve its operational preconditions. In this context, a trend in logistics is to improve logistical visibility both internally in a company and between companies in the supply chain, for instance, to make it possible to obtain more accurate information on demand issues (Lukka 2004). These partnership issues are emphasized in the Finnish nursery industry due to the outsourced final customer interface, which in most cases is in the hands of middlemen such as FOAs.

At present, benchmarking is also made in logistical practices. Thus, the best practices are selected, and companies applying them usually survive best in chaotic situations (Boyson et al. 1999). Here, benchmarking tools, such as the Supply-Chain Operations Reference-model (SCOR) (http://www.supply-chain.org/...), could be used to provide standard measures for evaluating companies' success in logistical processes (Lukka 2004). Finally, from a biological standpoint, there is a need for practical information about the success of seedlings grown from seed origins brought to a nursery unit from the area to which the seedlings will finally be planted. Altogether, the results of the research are hardly complete; and thus more precise information, for instance, on the topics listed above, may be needed.

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I

Economic Evaluation of Container Seedling Packing and Disinfection Machinery

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Rantala, J., Väätäinen, K., Kiljunen, N. & Harstela, P. 2003. Economic evaluation of container seedling packing and disinfection machinery. Silva Fennica 37(1): 121–127.

Productivity and costs of packing container seedlings were studied in a mechanised line for packing and disinfecting seedling trays. The hypothesis was that adequate cost-efficiency could be achieved when some common principles of mechanisation were applied. Results indicated that the unit costs are lower than those of manual packing, if these principles were applied and the annual number of packed seedlings exceeded 6 million. However, most of the nurseries in Finland are still too small to gain a real advantage from large-scale production.

Keywords mechanisation, packing, container seedlings, nursery technology, economies of scale

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1 Introduction

In Finland, about 90 per cents of all seedlings used for forest regeneration are container seedlings. Seedlings may be packed for silvicultural reasons, to keep the seedlings in good condition during the storing and transportation. On the other hand, packing could be done from a logistic point of view to minimise storage, handling and transportation costs. Therefore, the packing of seedlings is typical distribution packing (Soroka 1999).

In many branches of industry, the economics of scale has led to larger production units. With the extensive reforestation needed each year, some pressure exists to decrease the production cost and consumer price of seedlings. One way to seek cost-efficiency would be to enlarge the capacity of single nurseries and to mechanize and automate their production activities. When the need for a certain piece of nursery equipment is evaluated, the following aspects should be taken into account (Landis et al. 1994):

- Is this piece of equipment necessary to meet the biological needs of the seedlings?
- How much time and money will this piece of equipment save, relative to the savings in labour?
- How amenable is the task to mechanisation?
- Is time to complete the task a major consideration?
- Will the equipment be used for only a short time each year?
- Can the equipment be leased or borrowed?

When analysing the development of harvesters, Harstela (2000) presented the following principles for cost-efficient mechanisation and automation: 1) movements of machines are essentially quicker than manual ones, 2) several work elements could be done simultaneously, 3) many work functions and elements could be combined and done by one machine, 4) multi-processing could be completed, 5) continuous acting could increase efficiency, 6) information technology could be exploited, 7) quality of work could be improved and 8) good productivity, favourable cost ratio and high rate of utilisation could be achieved. In the packing and disinfection line studied many of the goals mentioned above were reached. In particular principles 1–5 were fulfilled, so based on these aspects, the line had potential for cost-effectiveness.

In this study, the aim was to investigate actual mechanised packing of container seedlings from the standpoint of cost-efficiency. The hypothesis used here was that the mechanised line for packing and disinfecting seedling trays is more cost-effective than manual packing and separate disinfection of seedling trays if the following requirements are fulfilled:

- Packing and disinfection operations are combined in the same line,
- Line speed is sufficient,
- Annual amount of packed seedlings is high (rate of capacity utilisation),
- The line is operationally reliable (technical availability)
- On the annual level there are complementary functions for production building and other expensive devices (for example, tractor).

In addition, a common hypothesis was that the advantage of large-scale production could not be reached until forest nursery units are relatively large. This could be one reason for the success of small-scale and by-business nurseries in the seedling business today (Petäjistö and Mäkinen 1999). In other words, the current nursery units of forest nursery companies may not be large enough to obtain advantages from large-scale production.

Table 1. Technical specifications of the seedling trays studied (Lännen Plantek-F 2002).

	Tray dimensions, mm	Cell volume, cm^3	No. of cells per m^2
PL 64F	384 x 384 x 73	115	434
PL 81F	385 x 384 x 73	85	549
PL 121F	386 x 384 x 73	50	820

The figure after "PL" refers to the number of cells per tray

2 Material and Methods

The mechanised production line for packing seedlings and disinfecting seedling trays, developed by Lännen Tehtaat Co. and Fin Taimi Co., was studied. The theoretical impacts of increasing the operation speed of the packing machine on productivity and unit costs were investigated for three different types of seedling trays (Table 1).

Machine interruptions and the ratio of unsuitable to suitable seedlings were observed as part of the packing process. Furthermore, the impacts of annual number of seedlings packed on unit costs were studied. The results were used to evaluate the costs and the need for rearrangement of labour on the packing line.

The most interesting element of the packing line was the automatic packing machine (Fig. 1), which was a prototype in operation for the first season. The trays were brought to the packing line in racks by a tractor. From the rack the seedling trays were moved manually (*worker 1*) to an input conveyor that simultaneously transferred them towards the packing machine and operated as a buffer storage.

First, the packing machine automatically released seedlings from the trays using a special seedling comb. After light horizontal compression, the machine element set the bunch of seedlings down into a small open-top cardboard box (OCB). A worker (*2*) calculated the unsuitable seedlings, and the OCB was filled (*worker 3*) to an objective number of seedlings. After it was filled, the OCB was moved towards final packing by an output conveyor. The next stage (*worker 4*) was to put two OCBs inside one cardboard storage box (SB), then to close the SB and finally bind it with a plastic strap. After binding, SBs were piled onto

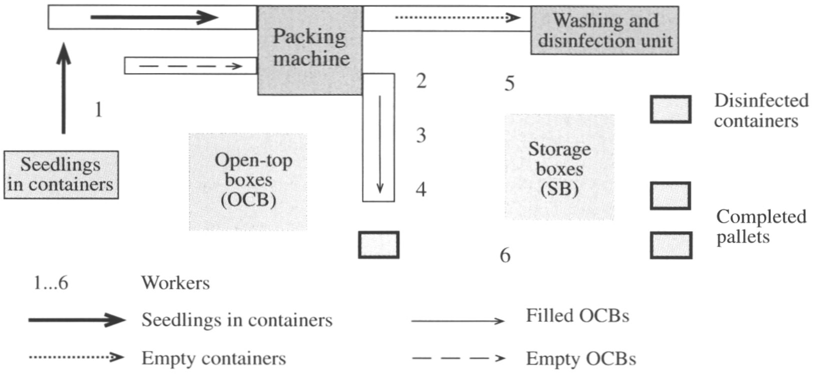

Fig. 1. Flow process chart of the packing line.

pallets (*worker 4*). Each pallet contained twenty SBs ready for storage or transport. Finally, the prepared pallets were wrapped with a plastic film (*worker 6*). *Worker 5* mostly prepared the SBs. All tasks of each worker are presented further in Fig. 2. After the seedlings were removed, the trays continued to the washing and disinfection unit. The trays were shaken to getting rid of seedling wastes, then washed and disinfected mechanically. At the end of the cleaning operation, disinfected trays were stacked automatically.

Video equipment was used to record the operation of the packing line. The recorded material consisted of the packing of Norway spruce (*Picea abies* L.) seedlings grown in 1260 units of Plantek 81F seedling trays (approx. 102000 seedlings). The workers were the same throughout the study. The total number of packed seedlings in the present season was 1.6 million. The method used in the time study was the work sampling method, which is a method of finding the percentage occurrence of a certain activity by statistical sampling and random observations (ILO 1979). The method is easy to use and also rather short time elements can be recorded manually (Harstela 1991). The sampling interval used was 2 minutes and the total recorded work place time 8 h 3 min. Thus, the time study data consisted of 241 observations. Here the percentage occurrence of different work elements, machine interruptions, idle times and rest pauses were recorded. The rate of utilisation of a tractor in the packing line was also estimated based on the recorded time data. Cost-efficiency of the packing line was determined by making cost calculations. The cost calculations were based on the arguments shown in Table 2. Annual depreciation was calculated by the straight-line method.

Table 2. Cost information of the packing and disinfection line.

Purchase price	100 900	€
Depreciation period	15	years
Salvage value	11800	€
Interest rate	6	%
Insurance	135	€/a
Total fixed costs	18 100	€/a
Number of workers	6	persons
Wages and social expenses	12.6	€/h/person
Other variable costs	24.3	€/h
Total variable costs	100	€/h

The fixed costs shown above included 30% of the total costs of the production hall and 10% of the fixed costs of the tractor. The packing line was located in a production hall that was also used for other activities. The tractor was fully employed by the packing line during the packing period. Other variable costs (24.3 €/h) consisted of hourly costs for the use of the tractor, and electricity, water, spare part and maintenance costs of the packing machinery.

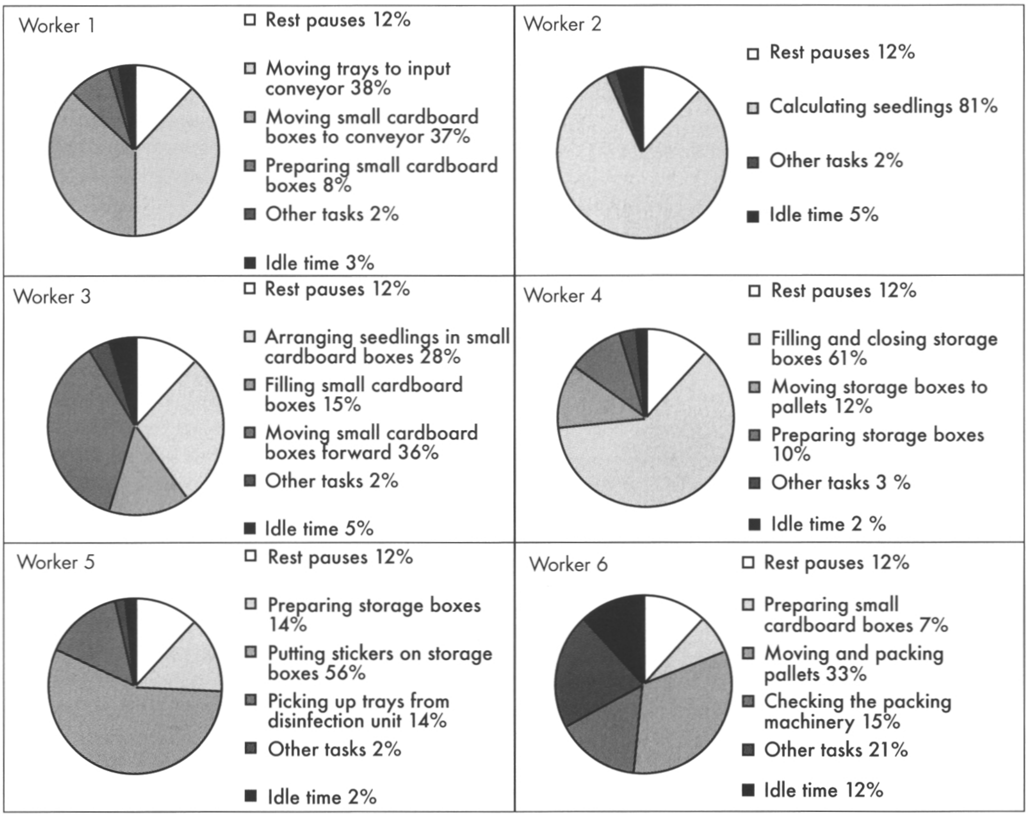

Fig. 2. Work place time (W_0) distributions.

3 Results

3.1 Time Study

Machine interruptions made up about four per cent of work place time (W_0). These interruptions caused idle time, in particular, for workers 2 and 3 (Figs. 1 and 2), who had 5 per cent idle time calculated from W_0. Other workers had compensative tasks so they were not so strongly influenced by interruptions. Worker 6 was the only one who had considerable idle time (ca. 8%), calculated on the basis of effective working time (E_0). It should be noted that, in addition to participating in the productive work, worker 6 was the foreman of the packing line. The percentage of different work elements for each worker is shown in Fig. 2.

3.2 Productivity and Unit Costs

As the cycle time of the packing line shortened, productivity was assumed to increase linearly. The theoretical output of the line was 15 300 seedlings per effective hour and 12 900 per work place hour (Plantek 81F, cycle time 19 seconds, machine interruptions 4% and rest pauses 12% of W_0). Productivity figures for different types of seedling trays are presented in Fig. 3.

Reducing the cycle time increased productivity (Fig. 3). The observed cycle time was 19 seconds, whereas the technical lowest limit for cycle time was 15 seconds. The theoretical seedling unit costs were calculated for three types of seedling trays (Plantek 64F, 81F and 121F). The impact of annual packing volume was also studied. The results of cost calculations are presented in Fig. 4. All tray types were used in the nursery but only

Plantek 81F was actually studied. Shortening of the cycle time from 19 seconds to 15 seconds decreased the unit costs by 6–16%, depending on the annual production volume and the type of seedling tray.

Hourly fixed and variable costs were independent from the tray type. Therefore, the share of fixed costs per seedling increased while trays with higher number of seedlings were packed. Increase in annual production volume reduced the share of fixed costs, respectively. The share of fixed and variable costs for each tray type according to annual production volume are presented in Fig. 5.

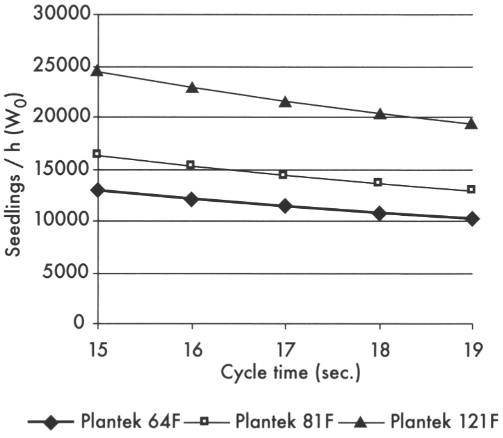

Fig. 3. Productivity of the packing line presented as a function of cycle time.

Unit costs do not include the costs accumulated by transferring disinfected seedling trays and completed seedling pallets. On the other hand, seedling transportation from the field to the packing line by tractor was included. Material costs, such those for seedling trays and cardboard boxes, were not included in these unit costs.

4 Discussion

Because the work rate of the production line was machine-controlled, the material investigated here may be large enough to estimate the productivity and to analyse the tasks of the workers. It is, however, very limited for estimating the machine interruptions. From the prototype machine it is difficult to obtain enough data for this purpose. Therefore a sensitive analysis was done. Doubling the amount of interruptions (8%) caused only a 2 per cent rise in costs.

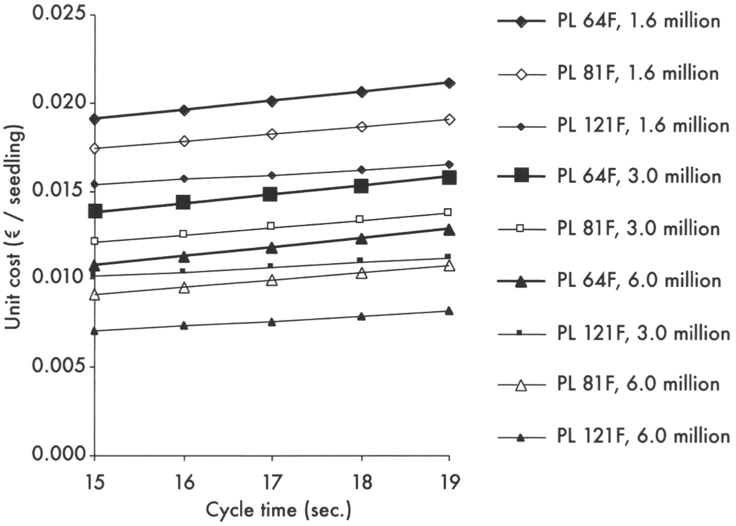

Fig. 4. The impact of the annual number of packed seedlings and machine cycle time on unit costs of seedlings grown in Plantek 64F, 81F and 121F seedling trays.

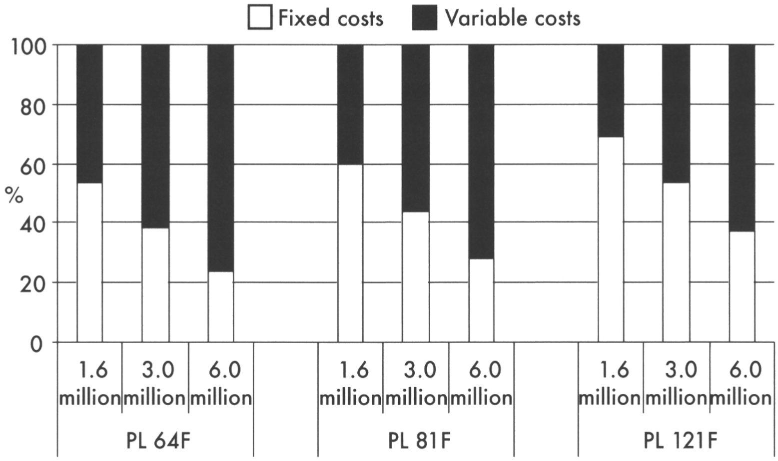

Fig. 5. The share of fixed and variable costs of the total packing unit costs while cycle time was 19 seconds.

The present cycle time of the packing machine was 19 seconds, and the productivity was 12892 seedlings per work place hour (PL 81F, machine interruptions 4% and rest pauses 12%). All six workers were needed for successful use of the packing line and the idle times were not significant. The workers usually had many parallel tasks to do. An exception was worker 2, whose only essential task was to count the unsuitable seedlings (97% of E_0). The proportion of useable seedlings in the trays varies between 80 and 99 per cent. As the deviation is so high, it is necessary to count seedlings and fill the seedling packages to guarantee a good-quality product. Seedlings could also be counted mechanically, in which case a mechanised counter would compensate for one worker. In the present study with an annual packing volume of 3 million seedlings, that would lead to savings of 2900 € per year. An equivalent investment with a 6% interest rate and a 15-year depreciation period would be about 31 600 €.

Disinfection of each seedling tray with the currently used detergents takes about 10 seconds. The present machine disinfected two trays at a time. Thus disinfection would not form a bottleneck in the packing line even if the cycle time would decrease from 19 seconds to 15 seconds. However, higher operation speed may increase the risk of interruptions, but the material used here was insufficient for estimating that effect. Nor could workers ability to manage their tasks faster be observed in practise. Thus the following estimations of cost savings may be optimistic. Theoretically, decreasing the cycle time from 19 seconds to 15 seconds would reduce packing costs by 6–16%, depending on seedling type and annual packing volume.

The packing volume for the year (2000) studied was rather low, only 1.6 million seedlings. Thus fixed costs made up large proportion of the total unit costs (53–74%). For that reason an increase in annual packing volume would reduce unit costs significantly. For example, doubling the annual packing volume up to 3.0 million seedlings would reduce unit costs by 25–32%. Furthermore, if the annual number of packed seedlings increased to 6.0 million, the savings in cost would be 39–51% of the present unit costs. These calculations assume that the technical rate of utilisation remains constant.

According to the practical experience of some nurseries, the average output per work place hour in manual packing is about 1500 seedlings per worker (Plantek 81F). This productivity includes counting seedlings and filling boxes. Stacking the completed boxes onto pallets and packing the pallets take about half of one worker's work place time (W_0). If the personnel costs are defined to be 12.6 € per hour, the unit cost of manual packing would be 0.009 € per seedling.

So that the unit costs for manual packing would be comparable to the unit costs for the packing line studied, they should include the costs of washing and disinfecting the seedling trays. Three workers wash and disinfect 350 pieces of Plantek 81F trays in one work place hour (Tervo 2001). In addition, a tractor with driver is needed for 50% of the washing time to move seedling trays to the washing location. By taking into account these expectations, the total unit cost of manual packing would be 0.011 € per seedling. Thus, mechanical packing apparently is not cost-effective, compared to manual packing, with present technology until the annual packing volume exceeds 6 million seedlings (Plantek 81F). These total unit costs do not include the costs of moving washed and disinfected seedling trays or the costs of moving the completed pallets to storage or to transportation sites.

The cost comparison proves that most of the nurseries in Finland are still too small to gain a real advantage from large-scale production. Relatively competitive unit costs, in addition to local supply contracts, could be one reason for the vitality of a relatively large number of small-scale and by-business nurseries. However, as all the hypotheses presented in chapter 1 come true, the packing line seems to be cost-effective alternative for manual packing. Some nursery managers have said that the critical point for cost-effective production is an annual production of 10 million seedlings. Taking into account that not all seedlings are packed, this idea seems to be reasonable for mechanical packing of seedlings.

Acknowledgements

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II

Effect of Seedling Production and Long-Distance Transportation Planning Strategies on Transportation Costs of a Nursery Company

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ABSTRACT

In Finland, the number of nurseries has been decreasing year by year, and it seems probable that in the near future this trend will continue. It can be assumed that greater economies of scale could also be achieved in Finnish seedling production by enlarging the size of production units [9, 10]. The management strategies used by a nursery company for long-distance seedling transportation were compared with different allocations of seedling production among nurseries. To determine the optimal transportation costs in different strategies for seedling production and planning of long-distance transportation, linear programming (LP) was applied. To manage spatial information, a geographical information system (GIS) was used. The current development towards seedling transportation managed by nursery companies seems to have marked advantages in the cost-effectiveness of transportation. The relative improvement in cost-effectiveness caused by centralized transportation strategy (CTS) compared to decentralized transportation strategy (DTS), which is the mostly used strategy in seedling transportation planning in Finland, varied from 13.0% to 36.5%, depending on the number of nurseries and the degree of specialization of production among them. These results will be useful for nursery companies and forest owners' associations (FOAs) when they evaluate the cost effects of production allocation, product specialization and systems of transportation management.

Keywords: *seedling, transportation, nursery, planning, GIS, linear programming, Finland.*

INTRODUCTION

In many branches of industry, the economics of scale has led to larger production units [e.g. 1]. It can be assumed that greater economies of scale could also by enlarging the size of production units [9, 10]. In Finland, the number of nurseries has been decreasing year by year, and it seems probable that in the near future this trend will continue. Finnish nurseries have traditionally been quite small, producing 3-10 million seedlings per year. Nurseries have mainly served local customers , and their production has been divided among many types of seedlings. For the sake of comparison, in northern Sweden seedling production is concentrated in very few nurseries and fewer seedling types are being produced. Although in Finland, development has also been in this direction, most nurseries are still rather small and the number of seedling types produced is large. A decrease in the number of nurseries unavoidably causes an increase in total transportation costs. Thus, to obtain as much advantage as possible from lower production costs, more information about the effects of production concentration on transportation costs, and the development of systems for transportation control and planning of transportation are required.

Linear programming (LP) is widely used in transportation planning [e.g. 6]. In forestry, optimization of transportation has naturally been related to timber transportation and, more widely, to timber procurement. Standard LP and its variations have been applied to timber procurement problems, where the goal has been to find optimal timber flows from procurement areas to mills [8]. Planning of seedling transportation with LP requires a somewhat different approach, but in some ways is also similar to timber transportation. Laakkonen [3] applied LP to the distribution of regional demand for seedlings among nurseries. During the implementation of that study, governmental organizations (Central Forestry Board, District Forestry Boards and National Board of Forestry) owned most of the nurseries in Finland. Today, the nursery business has been privatized. Most of the companies are operating as limited companies and usually owning more than one nursery. The customers of these companies are usually non-industrial private forest (NIPF) owners due to their dominance in the ownership of Finnish forests. Few NIPF owners located near nurseries acquire their seedlings directly from nurseries, but usually Forest owners' associations (FOAs) or nursery companies deliver seedlings to the central seedling stores of the FOAs. Today, however, the modes of operation for long-distance transportation of seedlings seem to be quite varied, and research is needed to find the most cost-effective applications.

In this study, seedling transportation of a nursery company was optimized in various business circumstances. Optimal costs for seedling transportation were compared in two strategic dimensions: firstly, centrally planned

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transportation by the nursery company was compared with decentralized transportation organized by the customers who order the seedlings from the nearest nursery unit independently of other customers. In practice, decentralization leads to a situation where, due to difficulties in growing seedlings economically to meet the demand in a certain market area, internal transportation is needed between the nursery units of a company. The second dimension studied was related to the number of nurseries used for seedling production and the strategy of allocating production among nursery units. The aim of this study was to quantify the effect of different management strategies for seedling production and transportation planning on the total costs of long-distance transportation in a nursery company. At the same time, a LP model is introduced as a tool for planning seedling transportation.

MATERIAL AND METHODS

The seedling-production and transportation-management strategies studied

The wide range of seedling types was compressed to the five most important: two types of container spruce (1-year and 2-year), bare-root spruce (2- to 4-year), container pine (1-year), and container birch (1-year). The following strategies for seedling production were used in this study (Table 1).

In strategies S1 and S3 all nursery units produced equal numbers and proportions of the 5 seedling types. In strategy S6 the whole production was concentrated to one large nursery. In strategy S2 five nursery units produced seedlings according to the current practice of the company studied (Table 2). Production allocations in strategies S4 and S5 are presented in Table 3.

Production strategies S1, S3 and S6 are rather theoretical situations. Strategies S4 and S5, on the other hand, describe potential situations in the near future. In all production strategies, the total number of seedlings produced was constant (27 million). The customers closest to the nurseries were supposed to pick up their seedling orders themselves directly from the nurseries. Therefore the number of seedlings in long-distance transportation (23.85 million) was lower than the total number of seedlings produced.

The two alternative strategies concerning management of seedling transportation were:

1) Transportation planning and management are centralized (CTS). Here LP was applied as a tool for planning long-distance transportations.

2) Each customer acquires seedlings individually from the nearest nursery unit (DTS).

Table 1. Seedling production strategies used in this study.

Strategy	**S 1**	**S 2**	**S 3**	**S 4**	**S 5**	**S 6**
Number of nursery units	5	5	3	3	3	1
Number of seedling types produced in one nursery unit	5	4-5	5	3-5	2-3	5
Degree of product specialization	None	Small	None	Medium	High	—

Table 2. The current production allocation of the company studied (strategy S2).

Strategy 2	Nursery 1	Nursery 2	Nursery 3	Nursery 4	Nursery 5	**Total**
Spruce (1-year)	4,000,000	1,000,000	1,000,000	500,000	2,000,000	8,500,000
Spruce (2-year)	3,000,000	2,500,000	1,500,000	500,000	1,000,000	8,500,000
Spruce (bare-root)	1,000,000	0	1,000,000	0	0	2,000,000
Pine (1-year)	1,000,000	1,000,000	1,000,000	500,000	1,000,000	4,500,000
Birch (1-year)	1,000,000	500,000	500,000	500,000	1,000,000	3,500,000
Total	10,000,000	5,000,000	5,000,000	2,000,000	5,000,000	27,000,000

Table 3. Production-specialization strategies S4 and S5.

Strategy S4	Nursery 1	Nursery 2	Nursery 3	Nursery 4	Nursery 5	**Total**
Spruce (1-year)	5,000,000	0	1,000,000	0	2,500,000	8,500,000
Spruce (2-year)	3,000,000	0	4,500,000	0	1,000,000	8,500,000
Spruce (bare-root)	1,500,000	0	0	0	500,000	2,000,000
Pine (1-year)	500,000	0	3,000,000	0	1,000,000	4,500,000
Birch (1-year)	1,500,000	0	0	0	2,000,000	3,500,000
Total	11,500,000	0	8,500,000	0	7,000,000	27,000,000

Strategy S5	Nursery 1	Nursery 2	Nursery 3	Nursery 4	Nursery 5	**Total**
Spruce (1-year)	5,000,000	0	0	0	3,500,000	8,500,000
Spruce (2-year)	4,500,000	0	0	0	4,000,000	8,500,000
Spruce (bare-root)	0	0	2,000,000	0	0	2,000,000
Pine (1-year)	2,000,000	0	0	0	2,500,000	4,500,000
Birch (1-year)	0	0	3,500,000	0	0	3,500,000
Total	11,500,000	0	5,500,000	0	10,000,000	27,000,000

the nearest nursery unit having an overcapacity of those types of seedlings. After seedlings are transported internally, the whole order can be delivered to the customer. Because all the seedlings are transported from the nearest nursery, the total external transportation costs are constant, regardless of the seedling production strategy. In other words, in order to keep up the current level of service, the current five units will remain as sale and depot locations, even if production there is abolished. In the CTS, there is no need for internal transportation.

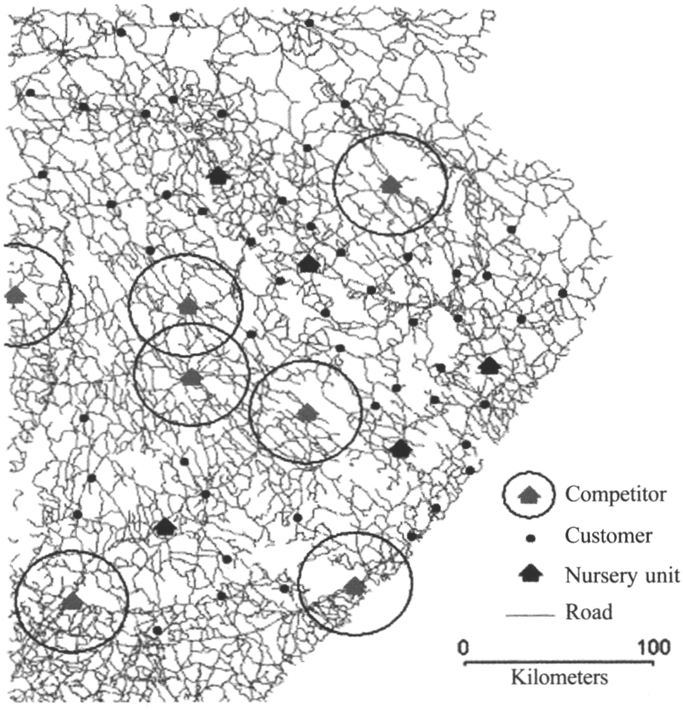

Figure 1. Main marketing area of studied company © Genimap Oy.

Utilization of GIS

The main marketing area of a real Finnish nursery company and the locations of its nurseries were chosen as the geographical basis of the study (Figure 1). The area contained five nursery units owned by the company studied and seven medium- or large-scale nursery units owned by other companies. The customers of the company within the marketing area were located according to areas of the municipalities, which in many cases correspond to the areas within which FOA operate. Fewer customers were located in those areas containing a large number of small private seedling producers, for instance, in the eastern part of the study area. Potential customers located within a 30-kilometer radius of nurseries owned by other companies were excluded from the study. A vector-based network of main roads and a raster-based map managed with the ArcView 3.2 geographical information system (GIS) were used as tools for measuring the shortest transportation distances from the nurseries to the customers. In practice, main roads used in long-distance seedling transportations are so homogeneous that here the cost-effect of the differences between different road classes was ignored. The eastern side of the road network is bordered by a national boundary. A situation in which the optimal route between nursery and customer would go out of the network seems very improbable.

Transportation costs and capacities

To obtain information on the seedling trade and on transportation practices, nursery managers, FOA officials and transport company managers were interviewed. This information was used to estimate transportation costs (Table 4) and the capacities (Table 5) of different transportation vehicles. Fixed costs (Table 4) were calculated on the assumption that the external transportation company owned the vehicles used for transportation. Thus, all vehicles were assumed to work year round and only a certain part of the fixed costs was assigned to seedling transportation.

Seedling demand

The distribution of seedling demand was also estimated on the basis of the interviews of nursery managers, because no precise data on seedling markets was available. The total demand for the various seedling types was determined to correspond to regional regeneration statistics produced by the Regional Forestry Centers. The figures used here for demand included only customers (88.3 % of the total production) that required long-distance transportation (Figure 2). Customers very close to a nursery typically pick up their seedlings themselves and transport them directly to the regeneration areas. Such customers were excluded from the analysis. The material included 51 customers. Seedling demand per customer varied between 100000 and 1100000 seedlings, the average being 470,000. The smallest number of seedlings of a certain seedling type ordered by a customer was 50,000.

Table 4. Transportation costs, including labor costs, for each type of vehicle used in this study.

Type of cost	Truck with a trailer	Pickup truck	Delivery van + trailer	Passenger car + trailer	Agricultural tractor + trailer
Terminal (US$/load)	108.1	55.3	16.7	16.7	30.7
Fixed (US$/load)	120.8	27.6	4.8	3.9	7.5
Variable (US$/km)	0.62	0.52	0.38	0.40	1.23

Table 5. Transportation capacity of each vehicle type used in this study (seedlings/load).

Type of seedling	Truck with a trailer	Pickup truck	Delivery van + trailer	Passenger car + trailer	Agricultural tractor + trailer
Spruce (1-year)	150,000	60,000	15,000	6,000	15,000
Spruce (2-year)	100,000	40,000	10,000	4,000	10,000
Spruce (bare-root)	75,000	30,000	7,500	3,000	7,500
Pine (1-year)	100,000	40,000	10,000	4,000	10,000
Birch (1-year)	75,000	30,000	7,500	3,000	7,500

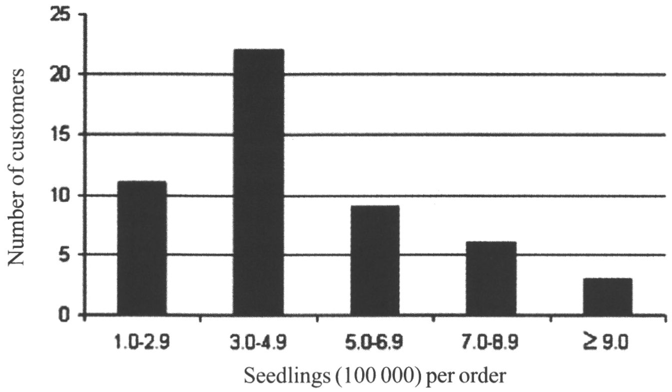

Figure 2. Distribution of the seedling demand in this study.

LP-model

To explore the effects of different production and transportation strategies, minimization of long-distance transportation costs was set as an objective of the study. Transportation costs depended on the volume of seedlings transported, type of seedlings, transportation distance and type of vehicle used for transportation. In the LP model, presented below, transportation costs were based on full vehicle loads. Thus, transportation costs were assumed to depend linearly on transportation distance. In reality, it is usually not possible to transport the seedlings ordered by each customer only in full vehicle loads. This would lead to the problem of non-linear optimization, which we wanted to avoid here. After linearization of transportation costs, the LP-model was formulated as follows:

$$\text{Min} \quad Z = \sum_{h=1} \sum_{i=1} \sum_{j=1} \sum_{k=1} C_{hijk} X_{hijk} \qquad (1)$$

$$\text{Where} \quad C_{hijk} = t_{hi} + f_{hi} + s_{jk} v_{hi} \qquad (2)$$

Subject to: **Non-negativity:**

$$x_{hijk} \geq 0 \qquad (3)$$

Customer orders:

$$\sum_{h=1} \sum_{j=1} x_{hijk} = d_{ik}, \qquad \forall i, k \qquad (4)$$

Production of seedling types at the nurseries:

$$\sum_{h=1} \sum_{k=1} x_{hijk} \leq p_{ij}, \qquad \forall i, j \qquad (5)$$

The following symbols are used:

h refers to the transportation vehicle
i refers to the seedling type
j refers to the nursery
k refers to the customer

Z = total transportation costs of the nursery company
C_{hijk} = the unit cost for seedling type i transported from nursery j to customer k by vehicle h
t_{hi} = terminal cost per seedling type i for vehicle h
f_{hi} = fixed cost per seedling type i for vehicle h
v_{hi} = variable unit cost for seedling type i transported by vehicle h
s_{jk} = transportation distance from nursery j to customer k
X_{hijk} = the amount of seedling type i transported from nursery j to customer k by vehicle h
d_{ik} = the amount of seedling type i ordered by customer k
p_{ij} = the production capacity of seedling type i in nursery j

The model consisted of 6375 variables and 280 constraints. The LP problems were solved with What's Best! 5.0 solver run with the Microsoft Excel 2000 spreadsheet [11].

In both strategies, it was assumed that customers could order all types of seedlings from the nearest nursery unit. Therefore, in the DTS, the nursery company must arrange internal transportation for the missing seedling types from

RESULTS

Cost calculations showed that, when relatively large numbers of seedlings were transported long distances, transportation by pickup truck, delivery van with a trailer, passenger car with a trailer or tractor with a trailer was more expensive than transportation by truck with a trailer. In other words, truck with a trailer was the most cost-effective vehicle for transporting seedlings more than 32 kilometers (Figure 3). Because all transportation distances in the model input exceeded 32 kilometers, the only vehicle appearing in the model output was the truck with a trailer. It should be noted that the costs in Figure 3 are based on full loads and all-year usage of the transportation vehicles.

To analyze the effect of seedling production and long-distance transportation strategies on transportation costs, twelve experiments were carried out. The current situation (strategy 2) with five nurseries using DTS was set as the reference value (100) for the comparisons. The results of these comparisons are presented in Figure 4 and Figure 5. The demand for seedlings was constant and the customers the same throughout the experiments.

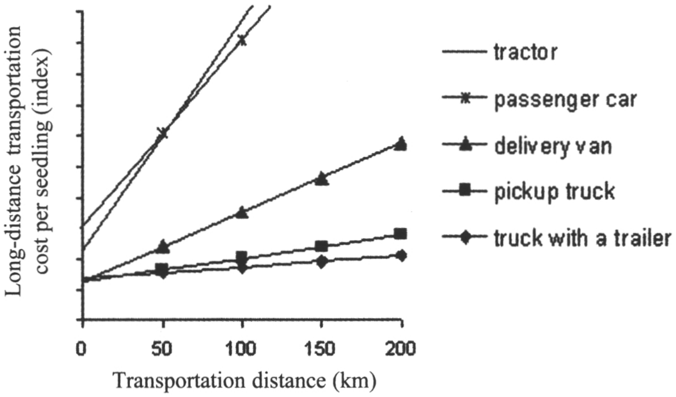

Figure 3. Cost curves including terminal, fixed and variable costs for seedling transportation with fully loaded vehicles.

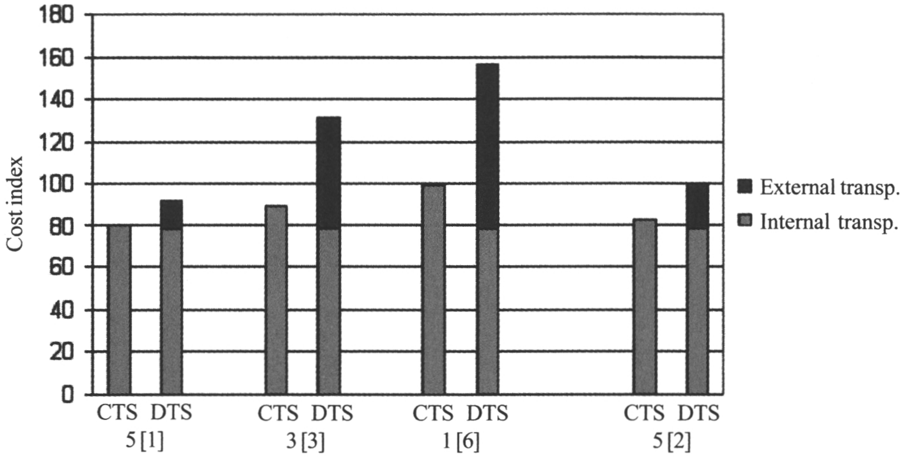

Figure 4. Effects of number of production units [production strategy number in brackets] on costs of long-distance transportation.

A decrease in the number of nursery units raised the total transportation cost due to an increase in the total transportation distance (Figure 4). The increase in cost was much smaller when CTS was applied to transportation planning. In this study, with the assumption of linear proportion of transportation cost and distance, the cost-effectiveness of CTS compared to DTS was the consequence of the shorter total transportation distance the company had to execute. In general, a centralized transportation strategy decreased transportation costs from 13.0 % to 36.5%, depending on the production strategies of the nurseries. For instance, in the case of equal allocation of seedling production among nurseries, reduction in the number of nursery units from 5 to 3 increased the transportation costs by 42.4% when DTS was applied and by only 12.5% when CTS was used in planning of transportations. The advantages of CTS compared to DTS were greatest when all production was focused on one nursery unit. It should be noted that a decrease in the number of nursery units means only putting an end to production, so that the original 5 units will continue as sales and storage sites.

The production strategy for three nursery units was selected for closer analysis in order to determine the effects of product specialization on transportation costs. To determine these effects three different strategies for allocation of seedling type production were studied. Studied strategies (3, 4 and 5) are presented in the material part of this study (Table 2 and Table 3). The same comparison as above was made for CTS and DTS. The current situation of 5 nursery units with small product specialization (strategy 2) was used as a reference index. The results of these comparisons are presented in Figure 5.

When the degree of product specialization increased, transportation costs also increased. The difference between no product specialization and high degree of specialization (Table 4) was 10.1% when CTS was used and 13.2% when DTS was applied (Figure 5). Thus, the increase in specialization slightly emphasized the advantages of CTS.

DISCUSSION

In Finland, the current development towards larger nursery units and seedling transportation organized by nursery companies seems to be very reasonable. Centralized planning of transportation makes it possible to optimize larger entities, thus leading to savings in transportation. In this case, a decrease in the number of nursery units from the current 5 (small degree of product specialization) to 3 (medium degree of specialization) increased the total transportation costs by 13.5 % when CTS was used in planning transportation and by 35.6 % when DTS was applied. The cost index for the first-mentioned current

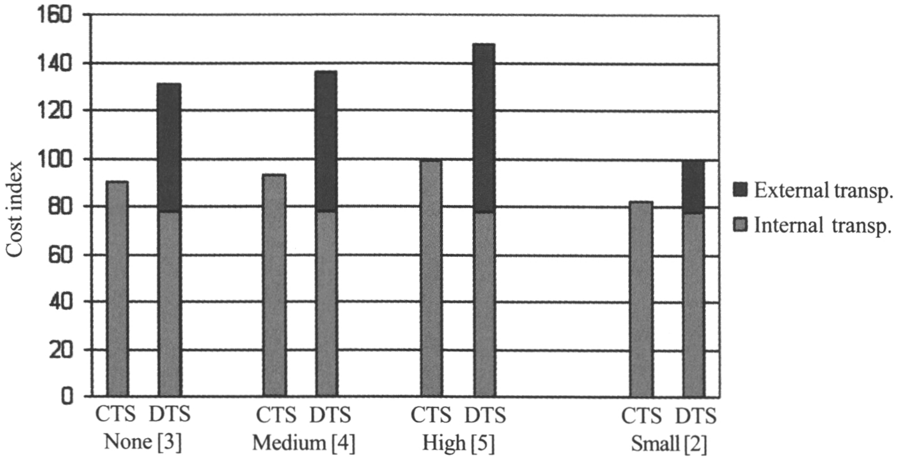

Figure 5. Effects of products specialization [production strategy number in brackets] on long-distance transportation costs.

situation (DTS) was 100 and for the latter situation of 3 nursery units (CTS) it was 93 (Figure 5). Thus, according to this study, the centrally planned seedling transportation for 3 units could become even cheaper than transportation from the current 5 units by applying DTS. Within the company, the effect of level of product specialization on transportation costs was not as great as the effect of number of nursery units (Table 6). The production strategies presented here are the views of the authors and do not reflect the policy of the company studied.

Table 6. Impact of production strategy on differences between CTS and DTS methods in terms of transportation cost.

Production strategy		**Cost difference between CTS and DTS, %**
Number of nursery units	Degree of product specialization	
5	None	**13.0**
5	Small (current)	**18.0**
3	None	**31.3**
3	Medium	**31.4**
3	High	**33.1**
1	—	**36.5**

In this study, decreasing the number of nursery units only means focusing production on fewer units as the former production locations will remain in use as sales and storage sites. In practice, a decrease in number of nursery units may slightly increase the proportion of seedlings transported long-distance in the CTS. This increase would consist of seedling orders to areas near abolished production units. Taking this increase into account may slightly reduce the advantages of CTS.

Naturally, evaluation of the optimal production and transportation strategies for a nursery company is much more complex than merely calculating transportation costs. First of all, the savings in costs achieved by a more effective system for managing transportation should be compared to the costs of acquiring, maintaining and using the system. Correspondingly, increased transportation costs caused by longer transportation distances with a smaller number of nursery units should be compared to the economic advantages achieved by larger production units. Nevertheless, according to this study and [9, 10], it seems that current development towards larger size of production units gives marked advantages from the standpoint of production cost-effectiveness; and an unnecessary increase in transportation costs could be avoided due to better planning of transportation.

Linearization of transportation costs might cause a slight underestimation of the total costs. This is mainly due to the assumption of full vehicle loads. In these theoretical calculations the last load to each customer is rarely full. Due to linearization, the transportation cost of seedlings in that last load is the same as the cost of the other seedlings transported to the customer. Nevertheless, we can assume that, in practice, several last loads can be combined and delivered to customers at the same time. Recent surveys in Finland have indicated that, on average, the total logistic costs account for ca. 10% of a company's turnover. Typically, transportation makes up ca. 40% of the total logistic costs [2]. In this study, depending on applied production and transportation strategies, operative optimized long-distance transportation costs varied between 1.6 – 3.1% of the nursery company's turnover.

Seedling production at nurseries can be directed to meet the forecasted demand in their marketing areas by using, for example, time-series data and harvesting statistics. In any case, growing tree seedlings in NIPF-dominated forestry is a production process in which production starts at least one year before the final demand for seedlings is known. To meet the regional demand, there can be some adaptation by transporting half-finished seedling material between nursery units. Seedling transportation is logistically challenging. Typical for seedling transportation are short periods of operation related to seasons and a need for special equipment. McKinnon [6] pointed out that physical distribution is increasingly becoming a specialist service that manufacturers purchase from outside agencies rather than organizing themselves. In this study, it was assumed that the transportation was purchased outside the company. Thus, all vehicle types were in productive work year round, and the fixed costs were not directed only to seedling transportation.

The results of this study are encouraging for long-distance transportation of seedlings by truck with a trailer. This is mainly due to the superior transportation capacity of truck and trailer combinations. Nevertheless, the transportation costs of truck with a trailer and pick-up truck were quite similar, and for both of these vehicles the sum of terminal and fixed costs was crucial. Thus, in terms of cost-effectiveness the order of these two vehicles might be sensitive to changes in cost calculation assumptions. The competitiveness of other vehicle types could be improved primarily through technical innovations that increase the transportation capacity. The results presented in this paper describe mainly the tactical level planning of transportation. It was assumed that seedlings transported long distances were shipped to FOA intermediate storage areas. Transportation from temporary storage to end-use areas is also needed. In practice, the interface between long-distance transportation and transportation to regeneration areas is indefinite: many of the seedlings can be transported directly from nurseries to regeneration areas. When seedlings are transported directly to regeneration areas, the unit size of each consignment would be much smaller than the units used in this paper. To distribute the seedlings to end-use areas as cost-effectively as possible, the convenience of each vehicle type should be re-evaluated. The applicability of vehicle-routing algorithms also needs to be studied.

Results of recent summer-planting studies with birch and spruce container seedlings have been promising [4, 5]. Thus, it seems that planting during the growing season will also become more common in the future. This development would lengthen the period of seedling transportation and bring the time factor to transportation optimization. In this context, dynamic linear programming [7] may become a useful method for solving tactical problems in seedling transportation. Further research is also needed to estimate the effects of linearization of the LP-model and applicability of more realistic methods for planning seedling transportation, such as integer-programming.

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III

Linear Programming and Mixed Integer Programming in Management of Seedling Transportation

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ABSTRACT

In this paper, the applicability of linear programming (LP) in management of seedling transportation was compared to that of mixed integer programming (MIP). In the LP model, presented in an earlier paper, a linear objective function was used as a surrogate for the actual objective function, which is intrinsically nonlinear. In the LP model, transportation costs were determined per seedling, whereas in the MIP model they were based on vehicle loads. When the number of transported seedlings within a certain period decreased, for instance, due to planting through the growth period, the computational accuracy of the LP model was clearly lower than that of the MIP model. Despite that, differences in allocation of orders between these two models were small. Thus, in the actual business situation of Finnish nursery companies, standard LP seems to be an adequate tool for management of seedling transportation. From the standpoint of cost-efficient seedling business, planting through the growth period increased optimal transportation costs markedly. In addition to the seedling business, these results can be utilized in other types of business dealing with analogous transportation problems.

Keywords: *nursery, transportation optimization, mixed integer programming, linear programming, Finland.*

INTRODUCTION

In Finland the forest nursery business has undergone huge changes during the last decade, and nursery companies are presently getting used to a new business situation. Companies have been privatized, domestic competition has increased and the seedling business has become more international. In addition, changes in legislation concerning the seedling trade have changed the role of middlemen, for instance, forest owners' associations (FOAs), making them more responsible to the end-users for the quality of seedlings. Therefore, the middlemen are at present more clearly the real customers of nursery companies. Therefore, in this study, the word "customer" refers to middlemen. At the same time, the number of nursery units has decreased, which has emphasized the importance of transportation as a part of the seedling business. In the future, general use of planting through the growth period (PTGP) might change customers' requirements, in particular, for seedling delivery activities. One possibility for nursery companies to respond to customers' requirements, and at the same time operate more cost-effectively, is to develop more advanced systems of transportation management.

According to recent studies, costs for seedling transportation could be lowered markedly by utilization of mathematical programming [10]. To study the effects of centralized transportation planning on transportation costs, Rantala *et al.* [10] applied standard linear programming (LP). In the LP model, transportation costs were calculated per seedling and based on the assumption of full vehicle loads. The advantages of LP are, for instance, short and fairly predictable solution times. LP as a method has proved to be practical especially as a tool for strategic and tactical level planning of transportation [9]. Nevertheless, for the problem examined in the earlier paper by Rantala et al. [10], it is likely that the accuracy of LP will deteriorate when the total number of transported seedlings is small compared to the capacities of the transportation vehicles. This is due to the fact that a linear objective function was used in the formulation as a surrogate for the actual objective function, which is intrinsically nonlinear because it involves both fixed and variable costs. When the applicability of different optimization methods to the optimization of seedling transportation was prefigured, a few aspects were considered, in particular, how long the transportation distances will be, what the transportation costs of fractional vehicle loads are compared to those of full loads and what are the sizes of seedling orders in proportion to the capacities of transportation vehicles. Here, to evaluate the applicability of LP by constructing an actual model for management of seedling transportation, integer programming (IP) is introduced. In the field of forest technology, IP has previously been used, for instance, in modeling the optimal use of log-stacking lift trucks at wood terminals [4]. Mikkonen [8] introduced mixed integer programming (MIP), an adaptation of IP, as a tool for choosing harvesting systems.

Mathematical optimization problems, which include integer restrictions, are usually difficult to solve and require a huge computing capacity and much time. With IP models, formulation is crucial in determining whether the problem is solvable, and what the solution time will be[6, 11]. Other important factors affecting solvability of

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the MIP problem and time required for finding the optimal solution are the type of software used and the options applied in simplifying and thereby accelerating the solution procedure [1]. Usually success in MIP relies on the use of specialized MIP software rather than generalized IP software. IP models can be classified according to the types of variables; in pure integer programming, all variables are restricted to integer values; and in a MIP formulation, certain variables are integers, whereas the rest are allowed to be continuous. Another classification criterion is the number of integer values allowed for single variables; binary (0/1) restrictions are used to indicate whether something happens or not, whereas general integer restrictions allow all integer values that are in a feasible solution area [11]. The MIP model introduced in this study included only general form integer restrictions. There are two general approaches for solving IPs: "cutting plane" methods and the "branch-and-bound" (B&B) method. The B&B has thus far proven to be the most reliable; and most commercial IP codes use it, but aided by some cutting plane features. In the most general terms, B&B is a form of intelligent enumeration [3, 11].

From the standpoint of cost-efficiency, one of the most important prerequisites for mechanized planting is good utilization rate of planting machines. This necessitates planting through the growth period (PTGP), which in Finnish growing conditions means about a half-year time frame. According to recent studies, biological preconditions for PTGP exist; and seedlings planted during the growth period have succeeded even better than seedlings planted traditionally before the growth period [7]. The most important effect caused by longer planting period on seedling transportation is that whole orders of seedlings cannot be delivered to customers at the same time. Including a time factor in transportation planning models is characteristic for dynamic LP (DLP) applications [2]. Nevertheless, modes of business, also in seedling production, have gone step by step towards customer-oriented supply chain management. Typically, in a customer-oriented business, seedling orders should be delivered to customers (middlemen) during the predetermined time period to enable the customers' success in the further delivery of seedlings and in the organization of planting work. For that reason, transportation periods are assumed to be independent of each other; in this paper, seedling delivery is not modeled as a dynamic problem.

The aim of this study was to ascertain the applicability of LP and MIP methods for planning of seedling transportation in various business situations. The dimensions of the production strategies of a nursery company are included in terms of the number of nursery units and by dividing transportation into different numbers of time periods. Therefore, the effects of PTGP on transportation costs are also quantified.

MATERIALS AND METHODS

This study was made with the spatial and numerical data used by Rantala et al. [10]. The geographical material consisted of the main marketing area of a Finnish nursery company (ca. 96,000 km^2). The company produced five different types of seedlings in five nursery units; all seedling types were produced in every nursery unit. The total number of seedlings included in analyses was 23,850,000, which was about 80% of the company's production. The transportation network connecting these 5 nurseries with their 51 customers consisted of a database of the Finnish main roads. In addition to these five units owned by the company studied, seven nursery units owned by competing nursery companies were located in the area. Customers located closer than 30 km to any of these 12 nurseries were supposed to pick up their seedlings themselves rather than having them delivered. Thus, all 51 customers included in analyses were located farther than 30 km from any nursery unit. Spatial data were managed by a geographical information system (GIS).

In experiments where transportation was divided into a certain number of periods, the rule of home-territory was used. The home-territory was a circular area of 100 km radius around each nursery unit of the company studied. Customers located in the home-territories (30 – 100 km from each nursery) were included in the analyses, so that each nursery always transported seedlings that ended up in its home-territory. The total number of customers located in the home-territories was 19, from which 3 were concurrently located in the home-territories of two nursery units. Seedling orders of these three customers were allocated optimally between the nurseries in whose home-territories they were located. The reason for the rule of home-territory was twofold; firstly, it imitated practice by allowing customers located near nurseries to do business with familiar nursery personnel; and secondly, it speeded up calculation of the MIP model.

Based on their good cost-efficiency in long-distance seedling transportation, the vehicles studied were a truck with a trailer and a pick-up truck [10]. The transportation capacity of each load of a truck with a trailer was 2.5 times more than the corresponding capacity of a pick-up truck. Terminal cost for a truck with a trailer was 1.95 times, fixed cost 4.38 times and variable cost 1.19 times higher than the corresponding costs for a pick-up truck. Terminal cost represents the cost of activities related to loading seedlings for transportation in the nurseries and unloading them at the intermediate storage places. Fixed costs, on the other hand, are the non-variable costs of ownership for the transportation vehicles. A variable cost is the constant cost-coefficient for a certain distance unit transported by a certain vehicle.

To compare the applicability of MIP and LP to optimization of seedling transportation in various business situations, the MIP model was built. The LP model studied is presented in more detail in [10]. The main difference between the models was that in the LP model the optimal transportation cost was a multiple of the theoretical cost per seedling, whereas in the MIP model the cost-effects of fractional vehicle loads were taken into account by adding integer restrictions for the number of vehicle loads transported. In addition, in the MIP model the terminal costs were assumed to increase linearly as a function of the used transportation capacity, which can be seen in the latter part of the objective function (Eq. 1). The first part of the objective function calculates transportation costs for transporting an empty vehicle load on a certain transportation route. Actually, the LP model [10] is a special case of this MIP model; in the LP model the ratio between the sum of the space requirement for all seedlings in a certain vehicle load and the commensurate transportation capacity of the vehicle always equals 1. The MIP model was formulated as follows:

Objective function – minimize the total variable and fixed costs of all vehicle loads plus the sum of terminal costs associated with all vehicle loads (Eq. 1),

$$Min\,Z = \sum_{t=1}\sum_{h=1}\sum_{i=1}\sum_{j=1}\sum_{k=1}\left[c_{hjk}\,l_{thjk} + \frac{r_h x_{thijk} p_i}{P_h}\right] \tag{1}$$

Subject to,

Non-negativity of continuous variables (Eq. 2)

$$X_{thijk} \geq 0, \quad X_{thijk} \in \mathrm{R} \tag{2}$$

Non-negativity of discrete (integer) variables (Eq. 3)

$$l_{thjk} \geq 0, \quad l_{thjk} \in \mathrm{Z} \tag{3}$$

Total commensurate vehicle capacity must at least equal the space required by all seedlings transported (Eq. 4),

$$\sum_{h=1} l_{thjk} P_h \geq \sum_{h=1}\sum_{i=1} p_i x_{thijk} \qquad \forall\, t,j,k \tag{4}$$

Total quantity of seedlings delivered must equal total seedling demand (Eq. 5),

$$\sum_{h=1}\sum_{j=1} x_{thijk} = d_{tik}, \qquad \forall\, t,i,k \tag{5}$$

The total quantity of seedlings delivered must not exceed the total number of seedlings produced (Eq. 6),

$$\sum_{t=1}\sum_{h=1}\sum_{k=1} x_{thijk} \leq S_{ij}, \qquad \forall\, i,j \tag{6}$$

Where,

t refers to the transportation period
h refers to the transportation vehicle
i refers to the seedling type
j refers to the nursery unit
k refers to the customer

Z = total transportation costs of the nursery company
c_{hjk} = full-load transportation cost without terminal cost from nursery j to customer k by vehicle h
l_{thjk} = number of loads transported from nursery j to customer k by vehicle h during transportation period t
P_h = commensurate transportation capacity for vehicle h
p_i = space requirement coefficient for seedling type i
x_{thijk} = number of seedling type i transported from nursery j to customer k during transportation period t by vehicle h
r_h = full-load terminal cost for vehicle h

d_{tik} = demand for seedling type i by customer k during transportation period t
S_{ij} = production capacity of seedling type i in nursery unit j
f_h = fixed cost per load for vehicle h
s_{jk} = distance from nursery j to customer k
v_h = variable costs per unit of distance for vehicle h

Transportation cost c_{hjk} consisted of fixed f_h and variable v_h costs (Eq. 7).

$$c_{hjk} = f_h + s_{jk} v_h \tag{7}$$

While the distance s_{jk} between nursery unit *j* and customer *k* was less than 100 km, customer *k* was assigned to nursery unit *j* according to the rule of home-territory. In this situation all seedlings to customer *k* were supplied by nursery unit *j*. Mostly for reasons of computational heaviness, the production-capacity restriction (Eq. 6) is not included in the MIP solutions, except for those dealing with the effects of linearization. When the production-capacity restriction (Eq. 6) was ignored, the production capacity of each nursery was determined by the total demand assigned to that nursery unit in the optimal solution.

The accuracy of the LP model deteriorates whenever the optimal solution includes such a number of seedlings for a certain transportation route that cannot fit exactly into full vehicle loads. While the number of transportation routes remains constant, a decrease in the total number of seedlings delivered will decrease the average number of seedlings transported per transportation route. The smaller the number of seedlings transported per transportation route is, the larger the relative difference in the unit cost per seedling between the LP and MIP models can be. These effects can be illustrated by examining the worst possible solution for the MIP model: Let the number of seedlings transported to *m* customers be *N*. The average number of transported vehicle loads per transportation route is denoted by *a*, and *L* is the transportation capacity for vehicle *h*. At first, *N* can be determined as follows (Eq. 8):

$$N = a\,m\,L_h \tag{8}$$

The worst solution for the MIP model will be achieved by transporting one seedling to *m-1* customers and the rest of the seedlings to customer *k*. The *Ceiling* function rounds a number up to the nearest integer. Taking Eq. 8 into account, the highest transportation unit cost u_{hjk} can be stated as follows (Eq. 9):

$$u_{hjk} = c_{hjk} \left[\frac{\left[(m-1) + ceiling\left(\frac{amL_h - (m-1)}{L_h} \right) \right]}{amL_h} \right] \tag{9}$$

Determination of the transportation unit costs of the MIP model according to Eq. 9 is presented in Figure 1, which also illustrates the principal difference between the LP and MIP models. In both models, the terminal unit costs were the same for all seedling types.

It can be assumed that planting through the growth period (PTGP) will become more general in the future. In such a situation, transportation of seedlings would have to be divided into a certain number of periods. Here, optimization experiments were carried out to quantify the effects of PTGP on the transportation costs of a nursery company. In these experiments, seedlings were transported in 1, 3 and 5 periods in the business situations of 1, 3 and 5 nursery units. Transportation was divided into 5 periods only in the case of 3 nursery units. Criteria for allocating transportation among different periods, which reflects a possible situation in the near future, were based on recent studies [5, 7] and on the opinions of professional seedling producers. In the three-period model solution, between 16% and 53% of the total number of seedlings were transported per period, whereas in the five-period model solution between 8% and 39% of all seedlings were transported per period (Table 1).

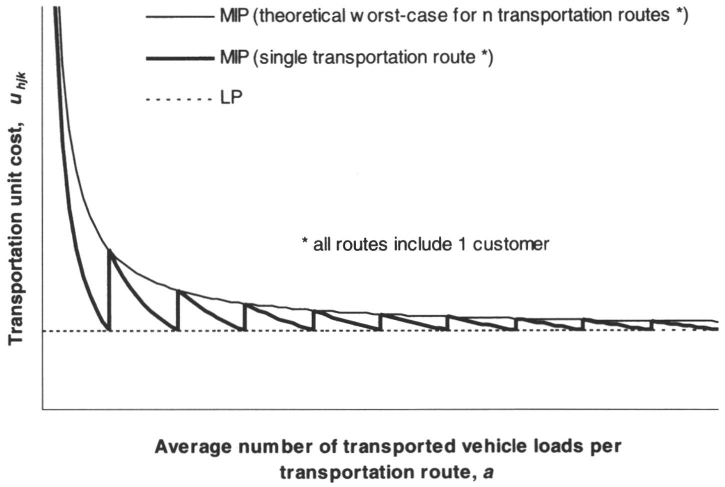

Figure 1. Principal unit cost functions for the LP and MIP models for a single transportation route and the theoretical worst solution function for n transportation routes optimized with the MIP model.

Table 1. Proportion of seedlings transported per period, expressed as a percentage of total annual seedling orders, in the one-period, three-period and five-period model solutions.

Number of transportation periods	Period 1	Period 2	Period 3 %	Period 4	Period 5
1	100	-	-	-	-
3	53	31	16	-	-
5	39	21	19	13	8

All computations were performed with a What's Best! Industrial optimization solver [12] in a PC with 260 MB RAM and Pentium III processor running under Windows 2000 operating system.

RESULTS

Effects of linearization

The process of converting a nonlinear expression to a linear expression is called linearization. The actual MIP model was used to quantify the effect of linearization on the accuracy of the LP model results in the business situation of three identical nursery units. Choosing the situation of three nursery units was based on the actual decision of the company studied to focus their main invests in the future on these three units instead of on the current five units. First, all transportations were optimized with the LP model. These optimal seedling shipments from nurseries to customers were picked up from the solution of the LP model and set into the MIP model as delivery restrictions. Thus the seedling shipments delivered were the same in both models, and the solutions could be compared merely from the standpoint of authenticity of transportation costs. The only optimization carried out at this stage with the MIP model was the allocation of seedling shipments between different vehicle types. As a consequence of linearization of the objective function in the LP model, total transportation costs calculated with the MIP model, later used as an index value, were 4.1% higher than the corresponding costs of the LP model (Table 2).

Experiments dealing with the effect of planting through the growth period (PTGP) on transportation costs of the nursery company, presented later, included the home-territory restriction. The effect of linearization on transportation costs in the LP model solution when the home-territory restriction was included is presented at the bottom of the Table 2.

Owing to longer total transportation distance, and due to relatively smaller terminal costs in the total transportation costs, the home-territory restriction increased the difference between the LP and MIP models slightly. The effect of the home-territory restriction on transportation costs of a single nursery unit depended mostly on its geographical location in relation to the destinations of the seedling orders. In this case, more customers were located in the home-territory of nursery 1 (7) than in the home-territories of nurseries 2 (4) and 3 (2). Thus, the transportation costs of nursery 1 decreased due to its central location, and the transportation costs of nurseries 2 and 3 increased (Table 3). The increase in transportation costs and also the difference between the LP and MIP models were greatest in the case of nursery 3 due to its outlying location.

The home-territory restriction reduced computing time considerably and, in some cases, was even crucial from

Table 2. Effect of linearization on transportation costs in the LP model solution compared to those calculated with the MIP model with and without the home-territory restriction.

Nursery unit j	1	2	3	Total	
LP model	35.6	33.8	26.5	95.9	Index
MIP model	36.8	35.1	28.1	100.0	Index
Total cost difference	**-3.2**	**-3.9**	**-5.5**	**-4.1**	%
LP (home-territories included)	33.6	34.2	29.7	97.4	Index
MIP (home-territories included)	34.7	35.6	32.0	102.3	Index
Total cost difference	**-3.2**	**-4.0**	**-7.2**	**-4.7**	%

Table 3. Effect of the home-territory restriction on transportation costs of a single nursery unit and on the total costs of the nursery company in the LP and MIP model solutions.

Nursery unit j	**1**	**2**	**3**	**Total**	
LP model	-5.72	1.17	11.91	1.58	%
MIP model	-5.69	1.24	13.94	2.25	%

the standpoint of solvability of the MIP model. For instance, optimization of seedling transportation in the production strategy of three nursery units with the MIP model took 10 h 41 min 5 sec without the home-territory restriction and 7 h 58 min 25 sec when home-territories were included. Due to their computational heaviness, each of the MIP model experiments was split into a few parts. The experiments were split by dividing customers into smaller groups and solving the transportation of one group at a time. Thus, restrictions on production capacities of nursery units could not be controlled during computation of the MIP model; and after the experiments presented above, these restrictions were excluded from both models.

Differences in optimal solutions of the models

At this stage, seedling transportation of the company studied was optimized with the LP and MIP models and the solutions were compared to each other. These experiments were done with the home-territory restriction but without the restriction on production capacities of nursery units. The effects of the home-territory restriction on solutions of the LP model naturally disappeared when the nursery-capacity restrictions were removed; optimal transportation performance of the LP model was based on the shortest possible total transportation distance of the nursery company. The main result of the comparison between the solutions of the models was that differences in allocation of orders among nursery units occurred only in the case of the current 5 nursery units. In the production strategies of fewer nursery units, the optimal solution was exactly the same in both models. Still, the effect of the number of nursery units on transportation costs, and on the cost difference between the solutions of the models was analyzed (Table 4).

As would be expected, transportation costs increased when the number of nursery units decreased. The differences in transportation costs between the solutions of the LP and MIP models were 2.72 – 3.86%, depending on the number of nurseries. The difference increased when the number of nurseries decreased. Two reasons for this were the relatively smaller proportion of terminal costs in the total transportation costs and longer transportation distance also for fractional vehicle loads in the production strategies with fewer nurseries. In this context, the relative difference between the models was also evaluated from the standpoint of optimal allocation of transportation among different vehicles. With this material, all transportation in the LP model solution was carried out by a truck with a trailer. To study the effects of vehicle allocation on transportation costs and on cost difference between the models, an experiment where all seedlings were transported by a truck with a trailer was also carried out with the MIP model. This experiment showed that, without taking into account the possibility to deliver smaller seedling shipments by pick-up truck, the relative difference in costs between the model solutions would be about 2% higher. Restrictions on the production capacities of nurseries were excluded from Table 4 but were included in Table 2. Thus, the effect of a restriction on production capacity can also be estimated. It is obvious that the total transportation cost is higher whenever any restriction on the production capacities comes true.

Table 4. Effect of the number of nursery units on total transportation costs and on the cost differences between the LP and MIP models when home-territory restriction was included. Comparison values are denoted by "-".

Number of nursery units	**Optimization method**	**Cost difference (%)**	***Cost index**
1	LP	-3.86	105.7
1	MIP	-	109.9
3	LP	-3.02	91.2
3	MIP	-	94.1
5	LP	-2.72	83.4
5	MIP	-	85.7

* Index scale is the same as in Table 2.

In this case, the restrictions on production capacities raised the total cost optimum by 6.8% when the LP model was used and 8.7% when the MIP model was applied.

In this context, weakening of the accuracy of optimal transportation costs in the LP model solution due to smaller number of seedlings included in optimization was studied by comparing it to the solutions of the actual MIP model. These experiments were carried out in the business situation of three nursery units. As can be seen in Table 5, the accuracy of the LP model clearly deteriorated when the number of seedlings included in optimization decreased. The cost-effect of dividing transportation into a different number of periods, due to PTGP, for instance, is presented in more detail in the next section.

Compared to the one-period model, the three-period model raised transportation costs by 9.2 – 11.8%, depending on the number of nursery units. The increase was slightly smaller in situations where the number of nurseries was larger. Correspondingly, the total transportation costs of the five-period model, which was applied only to the production strategy of three nursery units, were 19.3% higher than the total costs of the one-period model. The MIP model solutions included an optimal allocation of transportation between a truck with a trailer and a pick-up truck. The effects of different production strategies and number of transportation periods on the optimal utilization of these vehicles are presented in Table 7.

Table 5. Effect of the number of seedlings included in optimization on accuracy of the optimal transportation costs in the LP model solution.

Number of transported seedlings	LP (*cost index)	MIP (*cost index)	LP compared to MIP (%)
23,850,000	91.2	94.1	-3.02 %
12,640,500	47.8	51.3	-6.97 %
7,393,500	29.2	33.5	-12.93 %
3,816,000	14.3	18.9	-24.42 %

* Index scale is the same as in Tables 2 and 4.

Cost effects of planting through the growth period

To explore the effects of PTGP on transportation costs, seven experiments were done with the MIP model. In these experiments, seedling orders were divided into transportation periods (Table 1) and optimized in various production strategies. Due to the computational heaviness of the MIP model, five-period model was solved only in the case of three nursery units. Total transportation costs in different business situations are presented in Table 6.

As can be seen in Table 7, the proportion of seedlings transported by pick-up truck increased slightly when the number of nursery units increased. This was mostly due to shorter transportation distances between the nurseries and their customers. The optimal proportion of pick-up truck transportation increased more markedly when the number of transportation periods increased. This was mainly caused by the smaller number of seedlings transported per route. These effects were studied in more detail in the production situation of three nursery units (Table 8). In this case, transportation by pick-up truck

Table 6. Effects of the numbers of nurseries and transportation periods on transportation costs of the nursery company. Comparison values are denoted by "-".

Number of nursery units	Number of transportation periods	Cost difference (%)	*Cost index
1	1	-	109.9
1	3	11.77	122.9
3	1	-	94.1
3	3	10.30	103.8
3	5	19.26	112.2
5	1	-	85.7
5	3	9.15	93.6

* Index scale is the same as in Tables 2, 4 and 5.

Table 7. Effects of the numbers of nurseries and transportation periods on allocation of transportation between a truck with a trailer and a pick-up truck.

Number of nursery units	Number of transportation periods	Truck with a trailer	Pick-up truck
1	1	96.02 %	3.98 %
1	3	86.95 %	13.05 %
3	1	95.70 %	4.30 %
3	3	84.06 %	15.94 %
3	5	77.01 %	22.99 %
5	1	94.13 %	5.87 %
5	3	78.36 %	21.64 %

increased drastically when the proportion of seedlings transported made up less than 10% of the total orders. In general, the smaller the number of seedlings transported, the higher were the costs and the larger was the proportion of seedlings transported by pick-up truck (Table 8, Figure 2).

From Figure 2 it can be seen that as the number of seedlings transported during a certain period decreased, transportation unit costs increased exponentially. The increase in transportation unit costs seems to be very slight until the number of transported seedlings decreases to less than 12,000,000; from then on, the increase in costs is strongly accelerated. Transporting 3,100,500 seedlings (8% of the total annual demand), for instance, was about 1.4 times more expensive than transporting whole orders (23,850,000) during the same period. Naturally, the increase in costs varied among individual customer orders. Thus, Table 8 and Figure 2 are based on average-cost values of the material used in this study.

DISCUSSION

In the MIP model, the unused transportation capacity of each load decreased the total transportation costs in accordance with lower terminal costs. This assumption was based on the views of nursery managers, truck drivers and the author's observations of vehicle loading and unloading. In general, the terminal costs for full-vehicle loads were about one third of all transportation costs. In theory, due to less total time required for vehicle operation per load, fixed costs should also become slightly lower when the number of seedlings per load decreases. Nevertheless, that decrease in fixed costs is rather theoretical and here it was ignored. Therefore the fixed

Table 8. Effect of the number of seedlings transported within each single transportation period on periodic transportation costs and on optimal allocation of transportation between a truck with a trailer and a pick-up truck in the production strategy of three nursery units.

Period	Number of transported seedlings	Proportion of total seedlings orders	Truck with a trailer	Pick-up truck	*Unit cost index
1/1	**23,850,000**	**100 %**	**95.70**	**4.30**	**100.0**
1/3	12,640,500	53 %	89.65	10.35	101.7
2/3	7,393,500	31 %	79.39	20.61	115.4
3/3	3,816,000	16 %	73.93	26.07	130.2
Total 1-3/3	**23,850,000**	**100 %**	**84.06**	**15.94**	**110.3**
1/5	9,301,500	39 %	85.2	14.8	102.9
2/5	5,008,500	21 %	77.19	22.81	116.3
3/5	4,531,500	19 %	74.11	25.89	121.6
4/5	3,100,500	13 %	72.53	27.47	139.9
5/5	1,908,000	8 %	52.00	48.00	165.1
Total 1-5/5	**23,850,000**	**100 %**	**77.01**	**22.99**	**119.3**

* Index is not comparable to previous indexes.

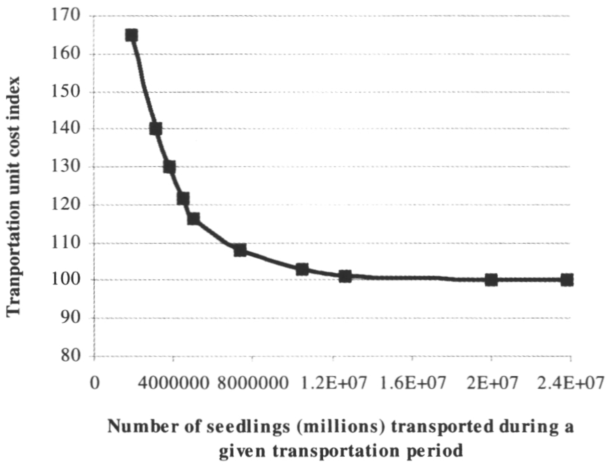

Figure 2. Effects of number of seedlings transported within a single transportation period on transportation unit costs.

costs of vehicles were considered to be constant.The relative difference in transportation costs between the solutions of LP and MIP models was slightly larger when the number of nurseries decreased. This was mainly due to longer transportation distances in the production strategies with fewer nurseries. On the other hand, of the total transportation costs the proportion of terminal costs was relatively smaller; and furthermore, transportation costs for seedlings transported in fractional vehicle loads may considerably increase the average unit cost for transportation. In practice, an important advantage of using the MIP model instead of the LP model might be the MIP model's ability to help operator avoid fractional loads that include only a few seedlings.

Despite the slightly greater difference between the LP and MIP model solutions in terms of transportation costs, the accuracy of the LP model improved when the number of nurseries decreased. In practice, the real advantage of MIP compared to LP appears when the optimal allocation of seedling orders among nurseries differs between the models. In the production strategy of five nursery units, which is the current strategy of the company studied, there were some differences in allocation of orders between two of the five nursery units, whereas the rest parts of the optimal solutions were the same. Altogether, these differences were not very great. From the standpoint of order allocation, in the production strategy of three nursery units, the minimum cost solutions of the models compared were exactly the same. Thus, the solutions would also be the same in cases of less than three nursery units. Therefore, it seems that the current geographical density of the Finnish nursery units owned by the same large-scale company is close to the limit from which (to more sparsely located nurseries) no additional value can be reached by applying MIP to management of seedling transportation instead of LP. Taking into account the fact that in Finland development seems to be going towards larger and more sparsely located nursery units, LP seems to be the most workable method for management of seedling transportation. In a theoretical situation, where the same company would own more nurseries in the area studied, the density of nurseries might be high enough to obtain a real advantage from utilization of the MIP model rather than the LP model.

With the PC and optimization solver used here, the LP model computed markedly faster than the MIP model did. While computing time for LP was only a few seconds, MIP took hours, even though the problems were computed in parts. In addition, splitting the calculation of the MIP model into parts made it impossible to control certain restrictions during calculation. For that reason, after evaluation of the effects of linearization on the differences in transportation costs between the LP and MIP model solutions, restrictions on production capacity were omitted from both models. Thus, other results described the situation where the optimal seedling shipments were not restricted by production capacities. Therefore, all nurseries were thought to be able to respond to seedling demand in accordance with optimized transportation plan. In practice, not all seedling production could be included in transportation optimization, and sufficient numbers of seedlings would be left as a buffer storage for orders coming after optimization and transported outside of the optimized transportation plan. Another reason for excluding a certain part of the seedlings from the optimization could be the nursery company's wish to carry out internal transactions between nursery units. The latter reason, in particular, might increase total transportation costs but could be reasonable, for instance, from the standpoint of production cost-effectiveness.

According to this study, the LP model introduced by Rantala et al. [10] is an appropriate tool for planning seedling transportation. The main prerequisite for successful use of the LP model is a relatively large number of seedlings transported within the same time period. In this study, the greatest weakness of the MIP model was the huge time required to obtain a solution. The need for solution time rose exponentially as the number of integer variables increased. The computational difficulty of MIPs is well known. Here it should be noted that the software [12] used was not specialized for solving MIP problems. In general, solution times for MIPs are more reasonable when specialized software, with an appropriate combination of features simplifying the solution procedure, is applied [1]. The procedure can be simplified, for instance, by accepting a tolerance of variation from the true integer optimal solution. Nevertheless, any simplification was not used in this study. With the PC environment used in this study, the MIP model seems to be an appropriate tool for smaller, operative level, optimization problems such as seedling transportation of a single nursery unit or a single transportation period. In addition, the MIP model can be applied successfully to optimization problems where the feasible solution area is carefully restricted, such as allocation of optimal seedling shipments in the LP model solution among different transportation vehicles. Altogether, the size of the MIP problem should not be expanded too much in practical use.

In context of exploring the effects of PTGP on transportation costs with the MIP model, the dynamics of transportation periods was included only in terms of restrictions related to periodical seedling demand; the model itself was not dynamic. The reason for this was the assumption of customer-oriented management of supply chain by the nursery company. Taking into account the whole delivery chain, including intermediate storage places to planting areas, an important quality factor affecting customer satisfaction is just-on-time delivery of seedlings. This means that delivery schedules for each transportation period are predetermined according to customers' requirements. In the seedling business, timing is crucial, in particular from the standpoints of keeping up good quality of seedlings during delivery and successful organization of the planting work. Transportation periods were assumed to be independent of each other, implying that the period in which seedling shipments occur has no effect on transportation costs. In practice, failures occurring in previous transportation periods could naturally affect the number of seedlings included in transportation optimization of subsequent periods.

The crucial factor in terms of transportation costs (Table 8, Figure 2) and accuracy of the LP model (Table 5) was the number of seedlings transported within a certain time period. Cost effects caused by PTGP on transportation costs were studied with the MIP model because of the low accuracy of the LP model in transportation problems with relatively small numbers of seedlings in proportion to the capacities of the transportation vehicles. Compared to results from one-period model, transportation costs were about 10% higher when seedlings were transported during three time periods and about 20% higher when transportation was divided among five periods. Mathematical modeling of seedling transportation is not currently used in Finnish nurseries. Thus, these results are still rather theoretical and hardly correspond to the practical effects of PTGP on transportation costs. Nevertheless, it can be assumed that the increase in transportation costs caused by PTGP would be even larger without careful planning of transportation. The number of transportation periods needed depends mainly on the organization of intermediate storage for seedlings. In the case of centralized storage, three transportation periods might be enough; but in the current situation with unclear organization and fuzzy responsibilities, at least five periods might be needed to guarantee good quality of seedlings. PTGP, and in particular, mechanized planting, involves many logistical challenges but also possibilities. For instance, an entrepreneur working with a planting machine could take care of centralized intermediate storage of seedlings, which would make it possible to cut out some existing but unnecessary logistical stages.

Neither the LP nor the MIP model takes into account the routing possibilities of customer locations. Nevertheless, the numbers of seedlings transported between nurseries and intermediate storage places are rarely smaller than a vehicle load. In theory, the last seedlings of different orders could be combined into the same vehicle load and routed optimally. In practice, larger intermediate storage places, also used in this study, are so far away from each other that routing might not be more cost-effective than single transportation to every intermediate storage place. Further, in this paper, seedling delivery from intermediate storage places to regeneration areas was not included in optimization experiments; intermediate storage place is a natural interface between the operations managed by a nursery company and its customers.

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IV

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

Juho Rantala

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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

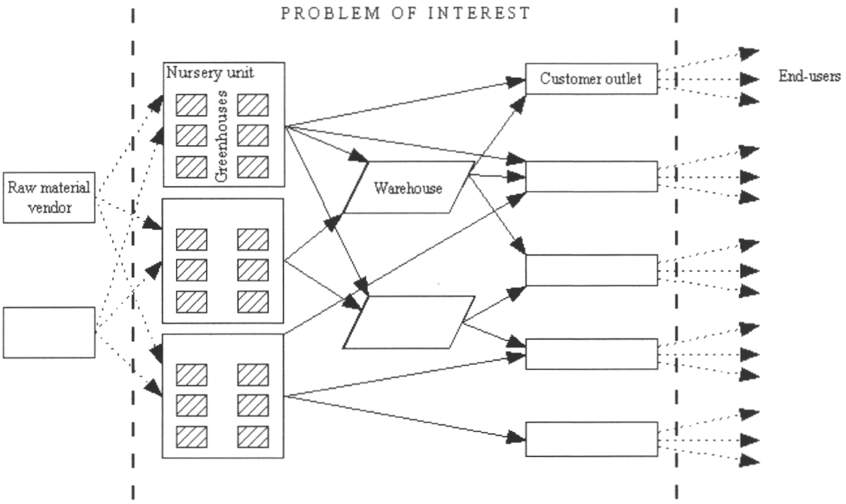

Fig. 1. Schematic illustration of a seedling supply chain.

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.

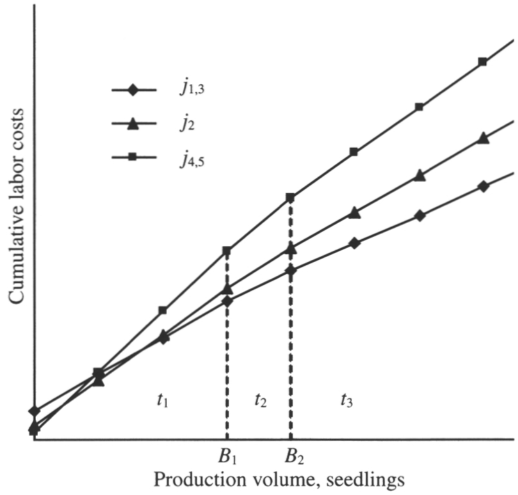

Fig. 2. Principles of concave cumulative labor cost functions for different types of nursery units (t_i = production stages 1...3, B_i = upper boundary of production stage t_i, j_i = nursery units 1...5)

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, $\begin{cases} h_1^E, h_2^E, ..., h_9^E \mid H_1 \\ h_{10}^E, h_{11}^E \mid H_2 \\ h_{12}^E, h_{13}^E, ..., h_{53}^E \mid H_3 \\ h_{54}^E, h_{55}^E, ..., h_{59}^E \mid H_4 \\ h_{60}^E, h_{61}^E \mid H_5 \\ h_{62}^E, h_{63}^E \mid H_6 \end{cases}$

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_{ghj}^E	capacity utilization rate of *existing* greenhouse h^E of greenhouse type g in nursery unit j
P_{ghj}^B	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

$$\sum_j \left(F_j Q_j + \sum_g \sum_h V_{gh} P_{ghj}^E + \sum_g \sum_h (V_{gh} + F_{gh}) P_{ghj}^B + \sum_t S_{tj} \left(X_{ijtw} + X_{ijtk} \right) \right) + \tag{1.1}$$

Warehousing

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

Transportation

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

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.

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

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.

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

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

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.

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

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).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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*.

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

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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