Article

Adaptive Model Building Framework for Production Planning in the Primary Wood Industry

Matthias Kaltenbrunner * , Maria Anna Huka and Manfred Gronalt

Institute of Production and Logistics, Department of Economics and Social Sciences, BOKU–University of Natural Resources and Life Science, Feistmantelstrasse 4, 1180 Vienna, Austria; maria.huka@boku.ac.at (M.A.H.); manfred.gronalt@boku.ac.at (M.G.)

* Correspondence: matthias.kaltenbrunner@boku.ac.at

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Abstract: Production planning models for the primary wood industry have been proposed for several decades. However, the majority of the research to date is concentrated on individual cases. This paper presents an integrated adaptive modelling framework that combines the proposed approaches and identifies evolving planning situations. With this conceptual modelling approach, a wide range of planning issues can be addressed by using a solid model basis. A planning grid along the time and resource dimensions is developed and four illustrative and interdependent application cases are described. The respective mathematical programming models are also presented in the paper and the prerequisites for industrial implementation are shown.

Keywords: production planning; sawmill; modelling framework; mathematical programming; integrated planning

1. Introduction

In production planning, the quantities to be produced are planned taking into account capacities, processes, the availability of raw materials and demanded products. In the primary wood industry, logs are used as raw materials in sawmills and processed into many intermediate products for further processing. These value-adding processes are usually carried out at one location. Three different value-added stages—sawing, drying and planing—are performed by a sawmill. Each of these process steps transforms the product wood into a new saleable product, namely, green timber, dried timber and planed timber. Transport and/or storage separate these individual production steps, for each of which there is capacity to comply, see Figure 1.

A typical characteristic of the primary wood industry is joint production, where, based on a common input, several products are produced using cutting patterns. This is a special challenge in the production planning of a sawmill alongside the natural raw material and the associated quality fluctuations. The quality of all manufactured products can only be determined with certainty after sorting and cutting the raw material. Production planning in sawmills is very diverse and mainly based on employee's experience.

The model framework presented here is intended to cover a broad spectrum in planning situations that can be used in a variety of ways. Not only the area of application, but also the way in which planning models are applied in the same company, vary. Individual departments expect varying results or require different analyses. The purchasing department, for example, wants information and support in sourcing the best mix of logs with regard to diameter and quality. The timber sales department, meanwhile, seeks to identify the products and quantities that can be additionally sold within existing contracts and customer requests. Figure 1 shows that this approach allows to choose

the desired degree of aggregation for planning. Hereby, the separate stages of the value chain processes can be considered collectively, individually or with machine precision.

Figure 1. Process view at possible aggregation stages in production planning models of the primary wood industry.

On the other hand, the selected planning horizon offers a dimension for refining the model framework. These two dimensions, in which the model framework application can move, correspond to an integration into the Enterprise Resource Planning (ERP) system or Manufacturing Execution System (MES).

Further analyses can be carried out taking into account the planning horizon and the frequency of planning (rolling planning horizon or iterative planning). In addition, special peculiarities of the system can be considered, see in [1]. Depending on the application, different or more precise information is required for planning. Data such as recipes, raw material deliveries, capacities, future sales and prices are required with increasing accuracy (for example, production recipe, process step recipe and individual machine recipe and occupancy time). To achieve this, the company needs a global data architecture that ensures consistent and continuous data preparation and access.

This paper presents an adaptive model building framework for production planning in the primary wood industry, which has been developed for industrial applications. In addition, its manifold application possibilities are demonstrated. In several papers on this topic, models are used that feature a high degree of similarity. However, these models are tailored to specific issues and companies, and therefore cannot be applied to different cases using a generic data structure. In order to ensure a versatile application, a generic framework model is developed. The underlying model paradigm considers as basic approach all process steps, value-adding and secondary processes including internal logistics, as sources of capacity consumption.

2. Literature Review

This section comprehensively describes the current state of knowledge on production planning models in the primary wood industry and arranges the existing literature into the classification of the introduced grid. In particular, the respective areas of application are worked out. For this purpose different models and solution methods were used and the existing literature is grouped accordingly in the following.

2.1. Linear or Mixed-Integer Programming

At first, works are considered which solve the problem by linear or mixed-integer programming up to optimality. A linear model of simultaneous production and sales planning for sawmills over several periods is proposed in [2]. The objective is to maximise the profit over the quarter of a

year under supply, production, marketing and inventory constraints. Another linear model for the aggregated production planning in several sawmills and over multiple periods is proposed in [3]. This model allows calculating production levels, outsourcing and inventory levels while meeting demand and maximising revenue. A linear programming model is used to plan sales and operations for a network of sawmills, including sawing, drying and planing phases, on a tactical level [4]. A planning horizon of one year with a period length of one week is chosen by the authors to maximise the gross margin taking into account seasonality. Different objective functions for lumber production with a planning horizon of 3 days are compared in [5]. To optimise harvesting, storage, transportation and production operations, while increasing the competitiveness of the forest products' supply chain, different customer inventory management policies are used [6]. For a group of sawmills and paper mills, the solutions of a market-to-order, vendor-managed inventory and a centralised planning approach are compared according to demand satisfaction and wood fibre condition. The authors solve mixed-integer programming models using a rolling planning horizon, in which four weeks in a row are planned for one year. Goal programming is used to identify the daily production plan considering several diverse optimal criteria [7]. First, the authors determine the conflicting goals of maximising profit and production and minimising raw material loss, inventory and unsatisfied demand using a trade-off matrix. Then, they solve the problem with weighted objective function using a mixed-integer linear program. A form-based postponement concept is used to develop a future production concept to close the gap between increasing importance of hardwood and lack of production concepts [8]. Therefore, new production processes for the solid hardwood production network, which also result in new material yields, are developed. The authors introduce a linear programming model to find the minimal cost for the supply network while fulfilling specific demands for one year.

2.2. Heuristic Approaches

Furthermore, there are papers which extend a linear model by a heuristic. Thus, larger problem instances can be solved in reasonable time. Set-up costs for sawing and drying are included in the tactical planning in [9]. The objective of the mixed integer model is to minimise the total costs for the furniture supply chain. The authors propose an efficient heuristic to solve the problem within reasonable time for industrial application. A linear model to reduce production costs at a sawmill is introduced in [10]. The authors use a rolling planning horizon for a two-month planning horizon with a more detailed first period, reflecting increasing uncertainty in data. Additionally, a heuristic is developed to compare with the optimal solution. The simultaneous planning of drying and finishing is studied in [11]. The authors plan and schedule these processes in the timber industry with the help of linear and constraint programming for 60 days. Several process steps in the lumber supply chain, i.e., harvesting, procurement, production, distribution and sales activities, are considered in [12]. The authors use a heuristic algorithm and mixed-integer programming to maximise the global net profit over the planning horizon of one year. A more recent work [1] deals with the influence of the stock levels on the optimal solution for production planning in sawmills. The developed model also contains approximations for set-up times for sawing lines and minimum feed quantities. In multi-periodic planning of 12 weeks, different planning frequencies and the evaluation of stock levels of round and sawn timber are addressed. The optimisation models can solve real problems in acceptable computing time. A mixed-integer linear program is used in [13] to plan production for five days with one day as the planning period. With this approach, suppliers are selected, the daily procurement of logs is planned, inventories evaluated, cutting patterns chosen and the volume of processed logs determined. The daily planning of sawmills with an integrated algorithm to generate suitable cutting patterns is investigated in [14]. The proposed approach simultaneously considers factors such as the availability of raw material, production capacity, demand and processing and set-up times. A mixed-integer linear program is used to solve the primary and secondary breakdown, which is extended by a remanufacturing process.

2.3. Simulation

Furthermore, an extension by simulation of the linear model for the solution of production planning was chosen by several authors. One of the earliest works is a simulation and front-end spreadsheet-based optimiser to determine the optimal log input mix while maximising economic return [15]. A linear model with included set-up times for the sequence planning of the production at a large softwood processing sawmill is used in [16]. The objective is to maximise the contribution margin. Furthermore, the author applies simulation to analyse the material flow and plans the occupancy of dry kilns. A framework for the elaboration and evaluation of management policies for production and transportation supply chains in the forest product industry is developed in [17]. The authors use an aggregated optimisation model for tactical planning over a year and discrete-event simulation for the detailed scheduling and routing on a weekly basis. The goal of the work is to identify the best combination of production-transportation flow and execution policies to optimise the profit in the network. A multi-level decision framework to support short- and medium-term sales decisions to improve service levels for high priority customers is provided in [18]. The authors use an order-promising model based on nested booking limits and solve this with a rolling horizon simulation. The performance is evaluated for a planning period of one year, during which short-term commitments can be made 8 weeks in advance.

2.4. Uncertainties

Other work focuses on possible uncertainties in production planning. A two-stage stochastic programming with recourse is used in [19] to design a forest industry supply chain. The authors apply a sample average approximation method based on Monte Carlo sampling techniques to maximise the expected corporate profits by considering several future market environments and deploying the best production-distribution network. Robust optimisation is used to minimise costs while planning production for a month with random yield [20]. Randomness in yields and stochastic demands is investigated in [21] with a scenario tree and multi-stage stochastic programming model when minimising the costs of production planning of a sawmill for a month. An accelerated scenario updating heuristic is used to solve a stochastic mixed-integer model with random yields and demands for the planning horizon of 30 days [22]. Set-up constraints are added in [23]. The authors use a scenario decomposition approach based on progressive hedging algorithm to solve the stochastic production planning problem. A two-stage stochastic linear program with random yields is used in [24]. Robust optimisation is used to maximise the economic benefit of the production with yield variability for a year, divided in monthly periods [25]. Robust optimisation is again used in [26] to schedule production for a sawmill plant subjected to final product demand and raw material supply uncertainty. The costs of inventory and backorder are minimised for a 6-week planning period. Two-stage stochastic models for production planning in sawmills with uncertainties in the supply of round wood is proposed in [27]. The authors apply these models with a rolling horizon by first determining the monthly log purchase and labour hiring over a period of 50 months without any connection through inventory. In a next step, the weeks of the first month are planned in more detail, including inventories, with the overall objective of minimising costs while satisfying demand.

2.5. Extended Models

A review of the use of operational research applications along the different wood fibre supply chains from the forest to the customers is given in [28]. The decisions in supply chain planning are categorised into three planning stages, ranging from strategic to operational planning. This categorization and models for the pulp and paper supply chain are described in [29], based on the supply chain planning matrix developed in [30]. A serious game about hierarchical procurement planning for the pulp and paper supply chain to develop understanding of short- and long-term impacts of decisions is introduced in [31]. Further along the supply chain there are other papers

dealing with production planning. A linear program for decision support in production planning for a wide variety of secondary wood product manufacturing plants is presented in [32]. The flexible model can be used for one-period and short-term (weekly to quarterly) planning and applied to secondary processing in the wood industry. Robust optimisation for the production planning in furniture settings is used in [33]. The objective is to minimise the total costs of production, inventory, backlogging, set-up, trim-loss and overtime. In addition to uncertainty in demand, the authors consider uncertain production costs. Several different simulation runs are conducted with different planning horizons. An agent-based simulation system for the production planning of two production lines in a rough mill to supply products for furniture, doors and window frames is proposed in [34]. Several simulation runs are tested for bottlenecks and advantages and disadvantages of using multi-agent paradigm in rough mill decision support is discussed.

Evidently, production planning in a sawmill has already been examined by several authors and solved with different approaches. An aspect that all these papers have in common is that they concentrate on a specific application, and therefore the proposed method is tailored to that. In addition, there are several objectives that can be pursued in the planning process. The contribution margin, profit or return can be maximised or the various costs, backorder or production time minimised, depending on the application and focus of the work. To summarise, in Table 1 the reviewed work is grouped according to its objectives, the solution method used, the field of application and the selected planning horizon.

The reference models provide a solid foundation for the proposed adaptive model building framework. On the other hand, this also represent an extension of these, as a systematically created model library is now developed that can be used for specific concrete applications. Stochastic aspects of planning in a sawmill are not examined at this stage. In a next step, and a possible extension of this paper, these can be added to the presented framework model. The main objective of the work is to present a modular, generic and flexible model for production planning in a sawmill. This model offers a versatile applicability for different problems based on a uniform data structure.

Table 1. Existing literature in the field of production planning in the primary wood industry. The objectives pursued, the methods used, the general scope of the models presented and the used planning horizon.

Paper	Objective	Method	Application	Planning Horizon
Alayet et al. [6]	Minimise costs	Mixed-integer programming model with rolling planning horizon	Forest products supply chain, different inventory management policies	month [week] for a year
Alvarez and Vera [25]	Maximise economic benefit	Robust optimisation	Production planning sawmill (sawing, drying, outsourcing and reprocessing)	year [month]
Bajgiran et al. [12]	Maximise global net profit	Mixed-integer program, heuristic	Plan lumber supply chain (harvesting, procurement, production, distribution and sales activities)	year [month]
Ben Ali et al. [18]	Maximise net profit	Order promising model based on nested booking limits, simulation	Sales and operations planning, customer service level	8 weeks [week] for a year
Broz et al. [7]	Weighted objective function of maximising profit, production, minimising raw material loss, inventory, unsatisfied demand	Mixed-integer linear program	Determine daily production plan satisfying several objectives	day [day]
Gaudreault et al. [11]	Minimise backorder	Mixed-integer program, constraint program, search procedure	Planning and scheduling drying and finishing	60 days [day]
Greigeritsch [16]	Maximise contribution margin	Linear model, simulation	Sequence planning for sawmill production, material flow simulation, dry kiln occupancy	14 weeks [1–2 weeks]
Huka and Gronalt [1]	Maximise contribution margin	Mixed-integer program, heuristics	Plan sawing, investigate loss of not following optimal plan, analyse inventory effects, different planning frequencies	12 weeks [2 weeks]
Jerbi et al. [17]	Maximise profit	Aggregated optimisation, discrete-event simulation	Selection of supply chain management policies for lumber supply chain network, tactical and operational planning	year [week], week [day]
Kühle et al. [8]	Minimise costs	Linear programming model	Develop future production concept using form postponement	year [month]

Table 1. Cont.

Paper	Objective	Method	Application	Planning Horizon
Lobos and Vera [27]	Minimise costs	Two-stage stochastic programming	Determine log purchase and labour hiring under uncertainties in log supply	50 months[month], 1 month [week]
Maness and Norton [2]	Maximise profit	Linear program	Production and sales planning for sawmills	quarter [month]
Marier et al. [4]	Maximise gross margin	Linear program	Production and sales planning for sawmills	year[week]
Maturana et al. [10]	Minimise costs	Mixed-integer program, heuristic	Production planning at sawmill with increasing uncertainty (rolling planning horizon, sub-periods in first period)	6 weeks [week]
Mendoza et al. [15]	Maximise economic return	Combined linear inventory and simulation model	Determine optimal lumber production schedule	10 h [hour]
Ouhimmou et al. [9]	Minimise costs	Mixed-integer program, heuristic	Furniture supply chain	year [week]
Pradenas et al. [3]	Maximise revenue	Linear model, simplex primal and dual, barrier method	Aggregated production planning for multiple sawmills and periods, determine levels of production, subcontracting and inventory	2–8 periods
Vanzetti et al. [13]	Maximise net benefit	Mixed-integer linear program, heuristic to determine cutting patterns	Multi-period production planning with integrated cutting pattern generation	5 days [day]
Vanzetti et al. [14]	Maximise profit	Mixed-integer linear program, heuristic to determine cutting patterns	Daily production planning with integrated primary cutting pattern generation	day [day]
Varas et al. [26]	Minimise cost (inventory, backorder)	Robust optimisation	Scheduling production for a sawmill with uncertainties in product demand and availability of raw materials	6 weeks [week]
Vergara et al. [5]	Minimise cost, waste, number of logs, production time, maximise profit	Linear model	Production planning sawmill, compare objective functions	3 days [hour]

Table 1. Cont.

Paper	Objective	Method	Application	Planning Horizon
Vila et al. [19]	Maximise expected corporate profits	Two-stage stochastic programming, sampling average approximation method	Design of forest industry supply chains, deploying production-distribution network	years [season]
Zanjani et al. [20]	Minimise costs (inventory, backorder, raw material)	Robust optimisation, stochastic programming	Sawmill production planning with random yields for robust customer service levels	month [day]
Zanjani et al. [21]	Minimise costs (inventory, backorder, raw material)	Multi-stage stochastic program, scenario tree	Production planning with uncertainty in the quality of raw materials and demand for a sawmill	month [day]
Zanjani et al. [22]	Minimise costs (inventory, backorder, raw material)	Stochastic mixed-integer model, accelerated scenario updating heuristic	Scheduling production for sawmills with randomness in yield and demand,	month [day]
Zanjani et al. [23]	Minimise costs (inventory and backorder)	Two-stage stochastic linear program	Randomness in yields modelled as scenarios with probability distributions	month [day]
Zanjani et al. [24]	Minimise costs (inventory, backorder, raw material)	Stochastic mixed-integer model, decomposition and cutting plane algorithms	Stochastic production planning in sawmills with randomness in yield and demand and set-up constraints	month [day]

3. Material and Methods

Production planning in the primary wood industry is diverse with a wide range of applications and uses. The framework model presented here is generically applicable. The various areas of application of the different departments are to be investigated on the same database. In the next section, the individual application cases will be discussed, and the modular framework model will be presented in the following order.

3.1. Application Field

To structure the framework and the modelling approaches Figure 2 shows that possible applications can essentially be created along two dimensions.

		Planning horizon [Period length]			
		Year []	Quarter [Month]	Week [Shift/Day]	Day [Hour]
Degree of aggregation	Entire production	1			
	Production steps		2	3	
	Machines				4

Figure 2. Grid in which possible application cases can move along the two dimensions, planning horizons with the specified length of a period length and degree of aggregation. Four specific application cases are additionally indicated.

The horizontal dimension describes the planning horizon and planning periods under consideration, which reflect the time period for the optimisation. A year without further subdivision into periods, a quarter with the subdivision into months, a week with the subdivision into shifts or days and a day with the subdivision into hours are determined as meaningful entities of this dimension. The vertical dimension describes the aggregation level of production, as illustrated in Figure 1. First, production is considered as a whole, from the arrival of logs until the sold products leave the sawmill. In the next step, the production is divided into three main value stream steps of the primary wood industry: sawing, drying and planing. After each of these steps, it is possible to sell the produced products. With the lowest aggregation stage, the production is subdivided down to the level of individual machines.

Tactical planning with a planning horizon of more than one year cannot be optimally planned to the minute on every single machine. The uncertainty of the future, customer orders and the availability of raw materials also contradicts an excessively long planning horizon in operational planning. In contrast, cutting planning and sequencing with set-up times can be carried out much more precisely and with a lower aggregation level. Due to the different requirements of several departments and the discussions with experts involved in production planning in a sawmill, four application cases of the framework model in Figure 2 have emerged:

3.1.1. Case 1: Procurement and Sales Support

This highest level of aggregation is used to support decisions at the management level: decisions such as the purchase of raw materials and their correct use, i.e., which products should best be made from the available raw materials. In addition, guidelines for the sales department can be derived from solving a model with this degree of aggregation. Information about unused raw materials and unsold products can also be obtained. A plan and benchmarks are developed through coordination between the departments involved and an iterative application of the planning.

3.1.2. Case 2: Production Preview

At a lower aggregation level, a production distribution network can be established that determines which raw materials are used at which locations and which products are manufactured. For this degree of aggregation, it makes sense to distinguish between the main process steps. The result is a rough production plan with capacity planning and aggregated dry kiln occupancy planning. Available-to-promise calculations can be made at this level. In addition, information that is more detailed can be obtained on unsold products and sales strategies can be adjusted accordingly.

3.1.3. Case 3: Operations Requirements

If the planning horizon is reduced while the aggregation level remains the same, further information can be derived. The result is a more precise production plan and a finer kiln planning. The model also provides information about the stock levels after the individual process steps. Logistical processes can also be planned at this level. The sales and production as well as the customer satisfaction can be planned with the corresponding model. The plans obtained at this aggregation level are used at an operational level.

3.1.4. Case 4: Order Release, Loading and Scheduling

In a final step with minimal aggregation, process planning can be carried out with machine precision. With this accuracy, the sequence can be planned and bottleneck analyses carried out. One of the results of this planning is a detailed occupancy plan for the dry kiln. These models are used on a day-to-day business for operational planning.

3.2. Planning Process

An important aspect for the successful use of this framework in a sawmill is the definition of an appropriate planning process and responsibilities, as many departments within a company have to collaborate. The workflow for the iterative planning process is illustrated in Figure 3. At the beginning of the planning process, the required data for the model used are selected from the ERP-system. This data can be forecasts, budgets, contracts and/or results from other optimisation runs. The result provides insights for the next step, which consists of analysing it with all involved departments of the company. Thereby, it is checked whether further adaptations are necessary to obtain applicable outcomes for each department. If necessary, additional constraints are added and a new production plan is calculated. This iterative sub-process is repeated until the needs for each department is satisfied. As a last step, the result is stored in the database and can be, for example, further used for sales, purchase guidelines or for future, more detailed planning.

Figure 3. Illustration of the new workflow for the developed iterative planning process with process and information flow.

3.3. Modelling Approach

Based on the models and application cases introduced and discussed in the section above, a linear modelling framework is developed that is not only versatile, but also permits a wide range of planning horizons and accuracies. Additionally, it intuitively covers the model specifications that arise from the framework specified in Figures 1 and 2. The model developed here also focuses in particular on production and the associated logistics processes within a sawmill. Different value-added stages, sawing, drying and planing can be planned in the desired degree of aggregation.

For the mathematical models different indices, parameters, and variables are used, which are described as follows. The indices of parameters and decision variables differ according to the respective application, so they are omitted for the sake of simplicity.

Indices

$p \in P$	Set of products
$d \in D$	Set of log types
$t \in T$	Set of periods
$o \in O$	Set of locations
$e \in E$	Set of production recipes
$s \in S$	Set of cutting recipes
$l \in L$	Set of drying recipes
$h \in H$	Set of planing recipes
$i \in I$	Set of sawing lines
$k \in K$	Set of kilns
$j \in J$	Set of planing lines
$v \in V$	Set of customers
$q \in Q$	Raw material types (logs, green timber, dried timber, planed timber)
$PG \subseteq P$	Set of green products
$PD \subseteq P$	Set of dried products
$PP \subseteq P$	Set of planed products

Parameters

Y	Yield of production with recipe in percentage
B	Assignment of raw material to recipe
N	Demand of product
R	Revenue of product
A	Available raw material
C	Costs
G	Duration of recipe per unit
M	Capacity for recipes
U	(Total) storage capacity

Decision variables

z	Volume of raw material processed with recipe
i	Stored volume
x	Sold volume
w	Backorder volume of product
f	Bought volume of product

The first model presented in this paper corresponds to Case 1, where no subdivision into planning periods is made and the entire production is considered in aggregated form. Additionally, no inventory quantities are taken into account.

Objective function (single period)

$$\text{Max} \quad \sum_{p \in P} \sum_{e \in E} R_p Y_{pe} z_e - \sum_{d \in D} \sum_{e \in E} C_d B_{de} z_e - \sum_{e \in E} C_e z_e \quad (1)$$

Subject to (single period)

$$\sum_{e \in E} Y_{pe} z_e \leq N_p \quad \forall p \in P \quad (2)$$

$$A_d - \sum_{e \in E} B_{de} z_e \geq 0 \quad \forall d \in D \quad (3)$$

$$z_e \geq 0 \quad \forall e \in E \quad (4)$$

Each application of the framework model uses the same objective function: the maximisation of the contribution margin. For this purpose, in Case 1, the revenues minus the costs for round wood and production are calculated in the objective function (1). Depending on what the model is used for, either the supply of round wood, the demand or both is fixed, while the other one is unlimited. Constraints (2) ensure that production is less than, equal to or greater than the given demand, depending on what is being investigated, i.e., best use of raw materials, demand fulfilment and sales planning. Constraints (3), on the other hand, guarantee that no more than the available round wood is consumed. The non-negativity of the decision variable is assured by constraints (4).

The next model introduced can be used for Cases 2 and 3, depending on the subdivision of the planning horizon. Here, a distinction is made between the individual production steps and locations but not yet between several machines. By integrating customers, which is more in line with Case 3, a more precise parametrisation of the quantity sold and penalty costs is achieved. Compared to the previous model, the maximum and minimum demand as well as the revenue and penalty costs per product are recorded customer-specifically. Thus, in case of insufficient supply of a product, the model decides for which customer the products are planned and for whom an unsatisfied demand arises.

Objective function (multi-period, multi production stages, customers)

Maximise

$$\begin{aligned}
 & \sum_{p \in P} \sum_{t \in T} \sum_{o \in O} \sum_{v \in V} R_{pv} x_{ptov} - \sum_{d \in D} \sum_{s \in S} \sum_{t \in T} \sum_{o \in O} C_d B_{ds} z_{sto} \\
 & - \sum_{p \in P} \sum_{t \in T} \sum_{o \in O} C_p f_{pto} - \sum_{s \in S} \sum_{t \in T} \sum_{o \in O} C_s z_{sto} \\
 & - \sum_{\bar{p} \in PG} \sum_{l \in L} \sum_{t \in T} \sum_{o \in O} C_l z_{\bar{p}lto} - \sum_{\bar{p} \in PD} \sum_{h \in H} \sum_{t \in T} \sum_{o \in O} C_h z_{\bar{p}hto} \\
 & - \sum_{r \in D \cup P} \sum_{t \in T} \sum_{o \in O} C_r i_{rto} - \sum_{p \in P} \sum_{t \in T} \sum_{v \in V} C_p w_{ptv}
 \end{aligned} \tag{5}$$

Subject to (multi-period, multi production stages, customers)

$$\sum_{s \in S} H_s z_{sto} \leq M_t^{saw} \quad \forall t \in T, o \in O \tag{6}$$

$$\sum_{\bar{p} \in PG} \sum_{l \in L} H_l z_{\bar{p}lto} \leq M_t^{kiln} \quad \forall t \in T, o \in O \tag{7}$$

$$\sum_{\bar{p} \in PD} \sum_{h \in H} H_h z_{\bar{p}hto} \leq M_t^{plane} \quad \forall t \in T, o \in O \tag{8}$$

$$N_{ptv}^{min} + w_{p,t-1,v} \leq \sum_{o \in O} x_{ptov} + w_{ptv} \leq N_{ptv}^{max} + w_{p,t-1,v} \quad \forall p \in P, t \in T, v \in V \tag{9}$$

$$\begin{aligned}
 i_{rto} &= i_{r,t-1,o} + A_{dto} + f_{pto} + \sum_{s \in S} Y_{rs} z_{sto} \\
 &+ \sum_{\bar{p} \in FR} \sum_{l \in L} Y_{\bar{p}rl} z_{\bar{p}lto} + \sum_{\bar{p} \in TR} Y_{\bar{p}rh} z_{\bar{p}hto} \\
 &- \sum_{s \in S} B_{rs} z_{sto} - \sum_{l \in L} B_{rl} z_{rlto} - \sum_{h \in H} B_{rh} z_{rhto} - \sum_{v \in V} x_{ptov} \\
 &\quad \forall r \in D \cup P, t \in T, o \in O
 \end{aligned} \tag{10}$$

$$\sum_{r \in D \cup P} i_{rto} \leq U_{oq} \quad \forall t \in T, o \in O, q \in Q \tag{11}$$

$$\begin{aligned}
 & x_{ptov}, f_{pto}, z_{sto}, z_{plto}, z_{phto}, i_{rto}, w_{ptv} \geq 0 \\
 & \quad \forall p \in P, t \in T, v \in V, s \in S, l \in L, \\
 & \quad h \in H, o \in O, r \in D \cup P
 \end{aligned} \tag{12}$$

As in case 1, the contribution margin defined in objective function (5) is maximised. This consists of the net revenue minus the costs for raw material, purchase of semi-finished products, sawing, drying, planing, inventory and backorder. Constraints (6)–(8) ensure that the required sawing, drying and planing time does not exceed the available operating capacity for each production step. Compliance with the minimum and maximum sales quantities, taking into account possible backorder, is guaranteed by the constraints (9). Constraints (10) describe the storage conservation constraints for logs and green/dried/planed sawn timber at the end of each period. This takes into account the available inventory from the previous period, incoming raw material, purchased semi-finished products, the quantity of raw material consumed in that period and the volume of products sold. Furthermore, constraints (11) guarantee that the stored volume of logs and green/dried/planed sawn timber does not exceed the available storage capacities. The non-negativity of all decision variables are assured with constraints (12).

The extension to the next model for application case 4 is done analogously and is therefore not explicitly mentioned for space reasons. Indices for the different machines are introduced. This allows different technologies with different yields, costs and machine occupancy times to be planned.

In addition, a transport variable is added, which reflects the flow of goods between the individual production steps and between production plants and customers. For these variables, constraints must be added to ensure that the available capacity is respected.

In contrast to the already existing models in the available literature, the individual application cases identified above can be solved with the same framework model and, above all, on a generic data structure, which becomes more detailed as the degree of aggregation decreases. This allows iterative planning at various levels of aggregation and with different planning horizons. Additionally, the models presented in this section are all linear and continuous and can therefore always be solved to optimum with standard LP solvers in reasonable time.

4. Industrial Application

The aim of this paper is to present an adaptive model building framework and its versatile applicability. When the framework is used for the first time, the model with the highest aggregation should be conducted first. This enables the user to get a feeling for the model, interpret the generated results and become familiar with the framework. Due to the high level of aggregation, the user is thus able to verify and validate on a small data set. The framework was developed in a more than two year cooperation with an ERP software company. Therein, many test instances have been provided by the company in order to formulate the comprehensive mathematical model descriptions and to define the generic data structure. In a further step, the degree of aggregation can be reduced under the same initial conditions as raw material availability and demand. As the level of aggregation decreases and the period subdivision becomes finer, the demands on the accuracy and completeness of the data increase. A well-designed and structured user interface combined with solid training is therefore crucial to build up acceptance for the new planning system and its processes in daily business.

Depending on the application of the model, different decision processes and actions can be supported. Additionally, the insights gained from the model can be further improved by iteratively adapting the constraints to the knowledge and needs of the different departments. In Table 2, the insights, adaptable constraints and resulting actions for the application cases are summarised. The application cases, procurement and sales support, production preview, operations requirements and order release, loading and scheduling are introduced in Section 3.1 and explained in more detail.

On the one hand, the optimal use of round wood can be planned. Therefore, a proposal for sales plan can be drawn up if a certain amount of raw material is available. By integrating minimum and maximum sales quantities, an optimised production and sales plan can be created systematically. The potentials in sales are therefore analysed and shown in a result-oriented way. Thus, active sales management becomes simpler and more efficient. On the other hand, the generic model can be used for cost accounting. Prices can be determined for new products. This corresponds to a holistic approach, as not only a single product, but the entire production is used for pricing. Additionally, the user can make a target–performance comparison by analysing and improving all decisions in the different areas. As the individual production steps are planned together, taking into account the respective capacities, the allocation of orders to different sites and possible additional purchase or missing quantities can be planned. This makes it possible to configure a supply network and identify key customers for whom a continuous supply must be guaranteed. Sequence planning of production with associated transport quantities and buffer storage can also be planned.

Table 2. Summary of the insights, adaptable constraints and supported actions, and decisions for the four application cases introduced in Section 3.1.

Case	Insights	Adaptable Constraints	Actions/Decisions
1	Best supply Sales quantities Unused logs By-products Used capacity	Min/Max quantity per log type Min/Max quantity per product Capacity	Purchase guidelines Sales guidelines Capacity planning
2	Approximate production plan Aggregated dry kiln scheduling Production quantities Unused logs Unsold by-products Used capacity	Min/Max quantity per product New cutting patterns	Sales guidelines Delivery promises
3	Production plan Used capacity	Min/Max quantity per product Stock quantities Minimal production quantities	Dry kiln scheduling External logistics
4	Production sequence scheduling Detailed dry kiln scheduling	Capacities	Bottleneck analyses Staff allocation

The innovative content of this flexible model is that these applications can all be carried out on the same data structure, only for a lower level of aggregation more precise or additional data is required. However, the data structure does not change. Consequently, an iterative application of the framework model for planning is possible, as described in Figure 3. In addition, the same model can be used in different departments; log procurement; production planning and sales; as well as in different hierarchical levels, management and department heads. This corresponds to an integration into existing ERP and MES systems. The interaction of the different hierarchy levels depends on the aggregation of the application. The exchange of information between the individual departments involved is also subject to the application cases. Figure 4 gives an overview of the information flow between the departments.

For the individual application cases, Table 2 shows the most important information that can be generated by iterative planning. On the basis of the application case procurement and sales support, this information exchange is explained in detail, see Figure 4. Additionally, a small interactive example with the integrated iterative optimisation and fictitious data is provided in the supplementary materials. In a first iteration, the best possible raw material purchase for a given demand is planned. The production calculated with the planning framework leads to purchasing guidelines for the round timber. In a further iteration, the optimal use of the fixed available raw material is planned and guidelines for sales are created. With the gathered insights from these first two basic scenarios the iterative planning process, as shown in Figure 3, is conducted, where each department analyses the output and defines additional constraints for the next optimisation run. In a final iteration of the planning, both the raw material purchase and the demand for sawn timber are fixed. At this level of aggregation, and with the longest planning horizon, the management is also involved in the planning to define framework conditions and receive information on budgets.

The use of optimisation models for simultaneous production and sales planning in sawmills seems long overdue, as this is already established in other industries. The integration of sophisticated analysis methods into application systems in the sawmill industry has hardly succeeded so far. Consequently, there is no industrial experience about the financial impact of such a system. However, the potential of optimisation compared to commonly used heuristic practices in production planning of wood industries is analysed in [1] and a large opportunity is identified. The generic models presented here are a first step towards such a versatile application and its integration into daily use.

Figure 4. General overview of interaction and information exchange between the individual departments included in the iterative planning process, as presented in Figure 3.

5. Conclusions and Discussion

Obviously, a suitable planning horizon, the planning frequency and the modus of planning, i.e., rolling wave planning, single-period or multi-period, have a great influence on the result. However, rolling planning in terms of the degree of aggregation, e.g., tactical and operational planning and their interdependence, also influences the solution and can significantly accelerate the solution finding process, especially when it is related to data availability and accuracy.

In the context of iterative planning with respect to the degree of aggregation and for the presented framework model in general, four main application cases that are relevant in combination with the degree of aggregation and the planning horizon have been identified, see Figure 2. However, some published literature differs from these. In Table 3, the existing literature presented in Section 2 is structured and added to the grid introduced in Figure 2.

Table 3. The existing literature structured along the two dimensions, degree of aggregation and planning horizon.

	Year	Quarter [Month]	Week [Shift/Day]	Day [Hour]
Entire production			Vanzetti et al. [13]	Mendoza et al. [15]
Production steps	Alvarez and Vera [25] Vila et al. [19]	Alayet et al. [6] Greigeritsch [16] Huka and Gronalt [1] Maness and Norton [2] Pradenas et al. [3]	Maturana et al. [10] Varas et al. [26] Zanjani et al. [20–24]	Broz et al. [7] Vanzetti et al. [14] Vergara et al. [5]
Machines	Bajgiran et al. [12] Jerbi et al. [17] Marier et al. [4] Ouhimmou et al. [9]	Ben Ali et al. [18] Lobos and Vera [27]	Gaudreault et al. [11] Jerbi et al. [17]	

This can be explained by the fact that a low level of aggregation with a longer planning horizon is no longer only optimally solved, but simulation and/or heuristics are also used to solve or at least provide suitable initial solutions and lower and upper bounds. For example, Jerbi et al. [17] use optimisation for tactical planning at a higher level of aggregation and simulation for operational planning, taking into account the results of tactical planning, to select supply chain management policies. Ouhimmou et al. [9] in turn assume that the demand data for a whole year are available without errors and are already known at the time of planning. A lower degree of aggregation can be achieved with the appropriate data for the model introduced by Mendoza et al. [15]. Another explanation for the deviations is that the authors use a rolling planning horizon to solve the problems studied in order to deal with the increasing uncertainty of data accuracy and availability. For example, see Ben Ali et al. [18], where sales and operations planning is done for one year, with the planning being divided into weeks for eight weeks at a time. Furthermore, the presented papers also answer questions that are not examined in this paper. Vergara et al. [5], for example, compare different objective functions for the production planning of sawmills and Vila et al. [19] focus on the design of forest industry supply chains.

The novelty of the presented generic framework model is the versatile applicability to solve different problems with the same model structure based on the same data structure.

6. Outlook

For the models presented in this paper, there are many possibilities of extension, use and application that can be investigated in the future. A first simple step of the extension, which makes the model especially usable for the application on the lowest aggregation level, is to add set-up times. Another application case of the framework model that has not yet been examined is the planning of delivery obligations for various customers. The model can further be extended to include uncertainties in raw material availability, recipe yields and demand quantities. In this case, it is particularly important to determine a robust production plan. Another possible extension of the model is the inclusion of flexible saw lines, which do not require predefined cutting recipes. An extension with a computed tomography scan to identify the best use of the raw material is another possible next step. This will allow the quality of the end products to be determined prior to the sawing process, which will have an impact on the utilisation of the round wood and the purchase of logs. Another still open field of application of the proposed model is reactive online production control. Finally, the model can also be used as a goal-chasing approach to optimisation by gradually adding more options to the model. These are selected from all available options, e.g., raw materials, recipes or customers, according to their contribution to the problem.

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