Flexibility in Planning and Operation of Sawmills

An Investigation of the Potential for Industrial Demand Response Using MILP Cost Optimisation Models

Master's thesis in Sustainable Energy Systems

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Abstract

Recent and future development of the electricity system calls for actions to match demand and supply. One action that this thesis investigates is the potential of demand response within the wood industry. The purpose is to investigate how this can be implemented with strategic planning and operation and what the implications are on both the sawmill and on the electricity system.

Efficient representation of the Sawmills has previously been performed with MILP models and is hence chosen as the main tool for this study. Together with four scenarios and data retrieved from industry partners, the study reveals the relation between overcapacity and demand to be determining the potential for flexibility. The results indicate that the chamber kilns are suitable to respond to short peaks (up to a couple of hours) in electricity prices whilst the progressive kilns can be used to manage and smooth variations of longer duration (in the range of 100 hours).

The magnitude of the flexible loads are approximate 5-60 kWh/h, which is not significant in the context of the Swedish electricity system. However, if the entire sawmill industry would respond such aggregate response can hav an impact on the electricity market. Further studies are recommended to include an investigation of the tipping-point of the profitability for flexible operation, i.e., what electricity prices or economic stimulation are needed to make the savings of the flexible operation larger than the expenditures.

Keywords: Sawmill, Flexibility, Mixed Integer Linear Programming, Demand Response, Sector Coupling, Production Planning, Energy System, Drying Kiln, Electricity, Cost Optimisation.

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Lastly, I want to thank my contacts at Södra Wood, Henrik Johansson and Tomas Bengtsson contributing as very valuable anchors to reality. Thank you for your persistent engagement in the difficult task of finding data.

I wish you all the very best of luck with your coming challenges and hope to meet you agian soon.

Josefine Kjellander, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

m^3l	Cubic meter loose
m^3sob	Cubic meter solid over bark
MC	Moisture content
MILP	Mixed integer linear programming

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1 Introduction

Decarbonization of the energy sector and increased end-use electrification are key measures to reach targets of the Paris agreement (IRENA, 2019b). The energy transition is likely to include a more widespread use of variable renewable energy sources, which are linked with different challenges. One of the challenges is to match the supply and demands of electricity, which will require more flexibility on both supply and demand sides to harmonize the variable production. Industrial demand response has emerged as one of the strategies that has the potential to supply flexibility. This means that an industry decreases or increases its electricity demand or supply in accordance with needs on the electricity system. Industrial processes with large energy consumption can have a large potential to contribute with demand responses with significant capacity, however, it can be limited by logistical and technical constraints.

This master thesis focus on a case of sawmills in the context of the Swedish energy system, however the ambition is to provide valuable insights for the sawmill and energy sector as a whole. The Swedish sawmill industry have an annual energy consumption of 8 TWh, which can be compared with Sweden's industrial energy consumption of 142 TWh annually (IRENA, 2019a; Swedish Energy Agency, 2021).

At sawmills most of the electricity is consumed during the main processes disintegration and drying (Anderson and Westerlund, 2014). The energy demands at the sawmill are however mainly as heat. The heat is self-supplied by combustion of byproducts in a bark boiler. In 2008 Swedish drying kilns used about 5 TWh heat, only to evaporate the moister in the timber (Andersson et al., 2011).

The significant energy use in the sawmill industry and their large inventories of intermediate products point out the need to investigate eventual merits from sector coupling by flexible operation of the sawmills and implications in the electricity system. In addition, there could be potential benefits that contribute to a more economic operation and efficient use of biomass. Such an investigation should however also consider the implications on the interrelated processes at the sawmill and the potential incentives for a sawmill operator to operate in such ways.

Various work have been conducted to develop the operation of sawmills, focusing on quality, material and/or energy efficiency, profitability and processing time. Many of them focus on isolated parts of the sawmills operation steps. To investigate flexibility in sawmills and its implications a systemic approach is needed.

Vanzetti et al. (2021) applies a systemic approach and includes the interrelatedness of the sawmills processing steps. They investigated the scheduling and batching of dry kilns with the application of a *Mixed Integer Linear Programming*, MILP, model. By combining the MILP models with *State Task Network* concepts they found an effective way of formulating a simple model formulation of the sawmill's complex system. This thesis uses a similar approach as Vanzetti et al. (2021) to investigate the flexible operation and planning of sawmills with an electricity cost minimization MILP model.

1.1 Aim and Purpose

The thesis aims to assess the potential and limitations for flexible operation and planning of sawmills. The purpose is to provide the forest industry and energy sector with insights of how their systems can influence each other and possibly find beneficial pathways for both.

To reach the aim the energy flows at the sawmill are mapped and the time dynamics of the processes are determined. Furthermore, the following specific issues and research questions are investigated:

- Construction of an energy systems model meeting the demand for timber products, yet, considering dynamic electricity prices.
- Given scenarios with variations regarding drying programs and kiln assignment of specific board types, how are electricity price variations influencing the operation and planning of sawmills?
- Estimation of the potential for flexibility with regards to energy, power and its possibility to reduce electricity costs.
- Which are properties are limiting and enabling the flexibility?

2

Background

This chapter will describe relevant terms and contexts, starting with the sawmills followed by the Swedish electricity system and flexibility. Lastly a brief introduction to MILP is given, which is one of the tools used in the method.

2.1 Sawmills

At a sawmill round timber is refined into boards and planks and the by-products woodchips, sawdust and bark are generated. The boards and planks can be used directly within construction and carpentry or further refined into laminated- and enhanced performance products. In 2010 there were 50-60 larger (annual production $> 100\ 000$ m^3) sawmills in Sweden (Andersson et al., 2011). In 2020 the Swedish sawmills produced 18,4 millions m^3 of sawn wood products of which 14,1 millions was exported (Alexandersson, 2020). The majority of the Swedish sawmills uses softwood i.e. spruce or pine (Svenskt Trä, 2021a).

The main activities at the sawmill are log disintegration and lumber drying (Svenskt Trä, 2021a). In addition, sorting, trimming and packaging are common production steps. Wood can have many qualities which are important to take into consideration in the refinement processes. Apart from the tree species are moisture content, MC, dimensions, knot occurrence and fiber direction taken into consideration during the sorting and refinement. Sorting and quality checking are thereof preformed, before, during and after the refinement. In addition to determine adequate refinement procedure, sorting has the purpose to assess quality and volume of the wood which are the price setting metrics of both received and refined wood. Figure 2.1 a illustrates a process diagram of the sawmill. In addition to the above mentioned production steps trimming and grinding is included, these are finalising steps to ensure adequate length and shape. Figure 2.1 b also includes a sankey chart illustrating the general distribution of in- and outgoing biomaterials at a sawmill.

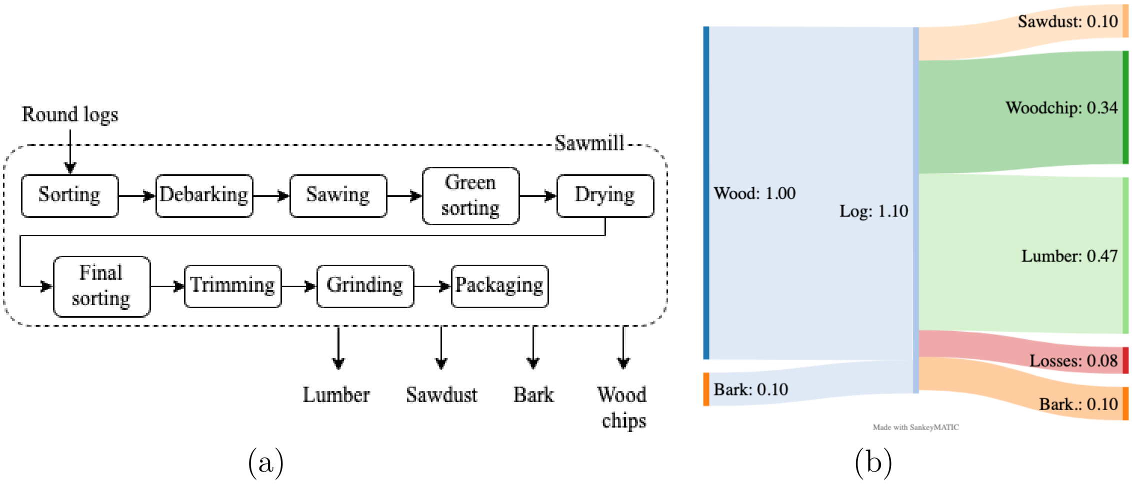


Figure 2.1: Process diagram of a sawmill including raw material and products (a) and sankey diagram describing the material flows in and out of the sawmill (Svenskt Trä, 2021a).(b) The flows are in m^3, with the basis of wood within the bark entering the sawmill which is normal practice in wood industry. Losses are caused by water removal (Andersson et al., 2011; T. Bengtsson, personal communication, 2022-02-04).

2.1.1 Log Disintegration

After the logs has been sorted into batches based on quality, size and properties, the they are fed to the disintegration line (Andersson et al., 2011). The line consists of a combination of the following equipment, debarker, band saws, circle saws, chippers and edge- and plane-reducers. The equipment is driven by electricity, and are often designed for a higher production rate than the process normally utilise to avoid interruptions in the production. A substantial part of the electricity supplied in the saw are to transportation of the materials between disintegration and sorting stages (T. Bengtsson, personal communication, February 4, 2022). During the log disintegration a majority of the byproducts are produced although some is produced during the finalising steps, grinding, planing and trimming.

2.1.2 Lumber Drying

Sawn timber has an MC of approximate 70 % before drying (Larsson, 2016). To protect the wood from damaging infestation, drying to an MC of at most 20% is necessary. The dominating drying technology in the Swedish wood industry is the drying kiln (Svenskt Trä, 2021b). Before entering the drying kiln the lumber needs to be stacked into organized and spaced piles. The spacing is created by sandwich lumber layers and stickers. In the kiln, heated air flows through the spacing in the piles and the MC decreases through water evaporation of capillary water and sorption (Keey et al., 2000). The flowing air acts as transportation media to both supply heat and to remove the evaporated water. The flow of heated air is essential to achieve an effective drying.

A drying kiln can be of either continuous or batch type and are called progressive and chamber kilns, respectively (Svenskt Trä, 2021b). Drying kilns of both types are equipped with electricity driven fans which creates the air flow. The heat is supplied in heat batteries which in turn are supplied with hot water from the bark boiler.

In the chamber kiln, the packages are stationary and the drying climate is changed in accordance with a drying program. The drying climate can be adjusted such that the lumber's drying stages presented in Figure 2.2 are considered (Andersson et al., 2011).

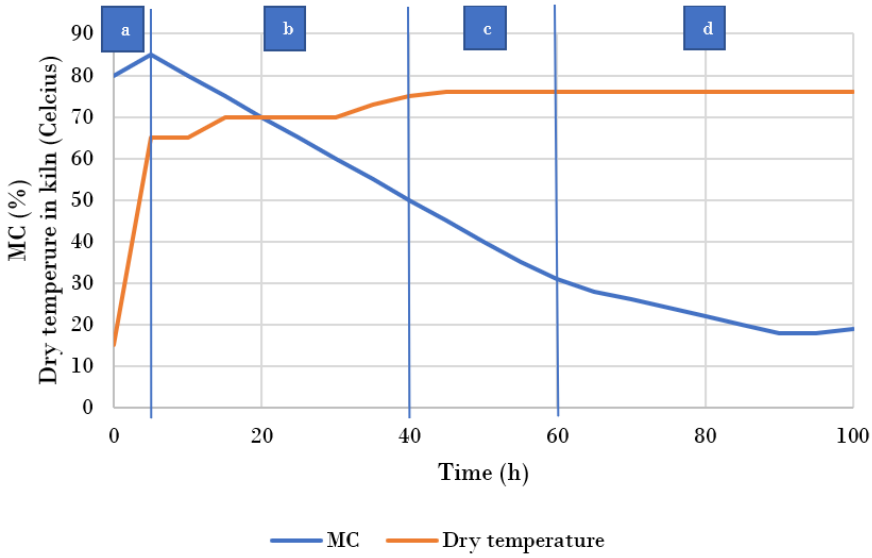


Figure 2.2: A plot of the dry temperature during a drying program together with the lumber's MC. The drying stages are indicated as a) Heat up, b) Capillary phase (removal of free water), c) Transition phase and d) Diffusion phase.

To adjust to the drying stages and apply different drying climates in the progressive kiln, the lumber packages are moved step-wise through it, thus are different drying climates applied in each position (Vikberg, 2015). The progressive kilns are continuous and commonly operates with heat and electricity loads around a steady state point.

Progressive kilns are designed for a higher productivity than chamber kilns and are also more efficient with regards to the heat consumption (H. Johansson, personal communication, May 25, 2022). The chamber kilns are however more efficient with regards to electricity consumption and has the benefit of giving the operator more control of the end product. Today, the chamber kiln is the most common in Sweden, however both types has a place in the Swedish wood industry and are likely to have substantial shares of the future production (T. Bengtsson & H. Johansson, personal communication, February 4, 2022).

Improper drying procedures can however lead to sever quality reductions(Keey et al., 2000). While wood endures drying it shrinks, which causes tensions within the boards since the volume change is not uniform throughout the lumber. The non uniform volume change is an effect of the woods morphology and mass transportation phenomenons. The tensions can eventually leads to cracks and lopsidedness of the lumber which in the worst case makes it unusable as lumber. The first hours of the drying is especially critical since it easily results in deformation caused by a fast drying in the surface of the lumber whilst the center of it have not even reached sufficient drying temperature. To mitigate this problem the lumber is kept wet by injection of steam or air suspended water in the first hours of drying. On the other hand it is during the end of the drying that the largest volume change occurs, making it critical to not dry the lumber too fast during this period.

To ensure a high degree of good quality products today's programs often are conservative with regards to throughput time and temperature (Svenskt Trä, 2021b). Drying of lumber with the thickness 50 mm takes approximately six days and 25 mm boards takes approximately three days. The time needed for drying depends on the initial and targeted MC. The initial MC is dependent on the ambient air moisture and where in the log the lumber originates from. The targeted MC for carpentry grade lumber is 8% and for outdoor and so called shipping-dry lumber it is 18%. Subsequent to the drying, the lumber needs to be conditioned in the kiln. During the conditioning some of the tensions are released and moisture differences within the pile are equalized, this take about 2-3 days. After this the drying is finished.

2.1.3 The Sawmill's Energy System

The central unit in the sawmills energy system is the bark boiler (Andersson et al., 2011). The boiler can either be designed to produce steam or hot water, where hot water is the most common at sawmills . The temperatures in the kilns are usually around 75 °C, which means that the hot water supply from boiler needs to be around 105-120 °C to allow for temperature drop.

The temperature level of the drying kilns heat demands leads to a significant amount of residual heat (Andersson et al., 2011). This heat is used for heating the office buildings and preheating/drying of fuel and in some places it also delivers heat to the district heating system. Additional energy related equipment which sometimes are used at sawmills are, flue gas condenser which can deliver heat at a level around 50-60 °C and economizer which preheats the water. If flue gas condenser is used it can usually cover the heat demand for the office buildings.

The energy demands in a sawmill are summarized in Figure 2.3. Approximate 12 weight-% of the fed material is used to cover the process heat demand (Anderson and Westerlund, 2014). The additional byproducts are sold for energy or material production within other industries (Andersson et al., 2011).

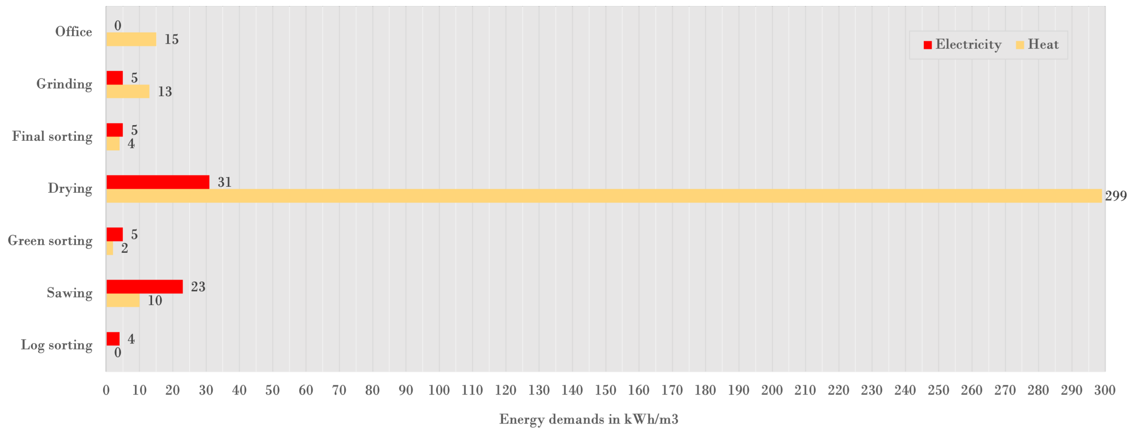


Figure 2.3: Energy demands of sawmill processes in kWh/m3 logs fed to the first sorting stage Anderson and Westerlund, 2014.

2.2 The Swedish Electricity System & Flexibility

In Sweden the energy mix and electricity spot price is determined by the day-ahead market Nordpool Spot (Nord Pool, n.d.). On the day-ahead market, supply and demand bids are collected at least 12h in advance of the days beginning. The operation schemes and electricity prices for the day in question are thereafter determined and published.

A high share of variable renewable electricity, VRE, can cause large variations in the netload (the difference between gross load and VRE generation) which is to be supplied from dispatchable generation leading to large variations in electricity prices (Göransson et al., 2019). The issues with mismatch of loads can occur on several time scales from seasonal to less than a second. The way of adaption has historically been to increased/decrease the supply from another adjustable energy source.

Introduction of flexibility is one alternative to deal with the variability, meaning that energy is shifted between times of surplus to times of deficit through actors adapting their demand or supply in accordance to balance the electricity demand and supply(IRENA, 2019b). Compared to an inflexible electricity system, increased flexibility leads to less curtailment of renewable electricity and the total installed capacity can be decreased (Göransson et al., 2019).

Flexibility can be provided on both supply and demand side, by charging/discharging of storages or by a change in either generation or demand (IRENA, 2019b). Since the characteristics of the load variations can have different time scale and magnitude this also applies to the flexibility measures (Lund et al., 2015).

Industrial demand response is a flexibility measure where the industry adapts their electricity consumption to harmonize the load differences (IRENA, 2019b). The adaption can either take place as a reduction by slow or shut down of the production in periods or as a shift in time when the electricity is consumed (Lund et al., 2015). Industries can preform shifting without loss of production if it has intermediate inventories and/or production speed which can be varied to catch up.

The business case for flexibility can simply be motivated by the difference in electricity price. Another alternative is to establish separate flexibility or power markets (Lund et al., 2015). A market for short term flexibility (within the hour) is in use all over Sweden, with the ancillary service market which is managed by the transmission system owner Svenska kraftnät (Svenska kraftnät, 2020). Markets for flexibility during longer durations are still on a regional scale and not widely applied (IRENA, 2019b).

2.3 Mixed Integer Linear Programming

Mixed integer linear programming, MILP, is a method which expresses problems by linear relationships with both continuous and integer variables (see e.g. Dotzauer, 2002, Chapter 4-5). Like normal linear programming problems the are MILP problems solved by optimisation (maximization or minimization of an objective) expressed in an objective function. The relationships constraining the problem make up the feasibility region of the problem. In a LP model the feasible region is continuous and solutions can be any point within the constrained area, but in MILP only discrete points within the area are feasible solutions. This makes MILP problems more complicated to optimise since the best possible solution is not necessarily in a vertex of the feasible region. A common way of solving MILP optimisation problems is the branch and bound algorithm.

The branch and bound algorithm solves MILP problems by relaxation of the integer variables and solves the relaxed problem by fixing one variable at the time starting with all variables relaxed (see e.g. Dotzauer, 2002, Chapter 5). When none of the binary variables are fixed the problem becomes a LP problem and the optimal solution to it becomes the algorithms lower bound (in the case of minimisation problems). Since a binary variable can only take two values there are at maximum two alternatives of optimal solutions while fixing a variable these are called branches. As long as the partly relaxed problem does not become infeasible another binary variable is fixed and the branching proceeds. The first optimal solution which satisfies all constraints of the unrelaxed problem becomes the algorithms upper bound. The solutions from other branches are thereafter obliged to be within the bounds of the upper and lower bound in order for further branching. Otherwise the branching continues finding infeasible and feasible model setups of binaries and solutions within and outside the optimal solution bounds. If another solution also satisfies all constraints of the unrelaxed problem and is within the bounds, this solution becomes the new upper bound. When the difference between the upper and lower bounds are within a given tolerance the algorithm stops and the unrelaxed problems final optimal solution is given as the final upper bound.

3

Method

To answer the research questions a MILP model which minimises the cost of electricity given a demand of lumber is formulated. The model aims to display the potential for flexibility and the consequences of that on the production. To reveal these effects an electricity price vector with high degree of fluctuations is introduced together with scenarios which varies model's ability to deviate from normal production procedures.

The model is implemented in GAMS and solved with IBM software Cplex 20.1.0 (IBM Corp., 2021; GAMS Development Corp., n.d.). A description of the model's formulation is presented and then the applied scenarios and data handling are described.

3.1 Model Formulation

The model represents the sawmill's production steps with the equations describing material and energy balances of each operation over a set of time steps, T. The model is formulated such that the first time step follows the last, meaning that the model status at the last steps are used as initial status. A list of sets, parameters and variables which are used in the model is presented in Table 3.1.

Table 3.1: List of sets, parameters and variables included in the model.

Sets	
T	Time, t, $(t_1, t_2, ...t_n)$
M	Matters, m, ($logs, wet\ side\ boards, wet\ center\ boards, dry\ sideboards, dry\ center\ boards, bark, sawdust, woodchips$)
P	Processes, p, ($saw, boiler, progressive\ kiln\ for\ side\ boards, progressive\ kiln\ for\ center\ boards,\ chamber\ kiln\ stage\ 1\ for\ side\ boards, chamber\ kiln\ stage\ 1\ for\ center\ boards\ chamber\ kiln\ for\ side\ boards\ stage\ 2,\ chamber\ kiln\ for\ center\ boards\ stage\ 2$)
U	Utilities, u, ($heat,\ electricity$)
I	Inventories, i, ($woodyard,\ wet\ lumber,\ dry\ lumber,\ byproducts$)

Subsets	
P^c	Chamber kilns in P
P^p	Progressive kilns in P
M^{bd}	Dry boards in M
M^b	Boards in M

Parameters	
p_t^{el}	Electricity price at t
Cap_{pm}^{max}	Maximum capacity of process p
Cap_{pm}^{min}	Minimum capacity of process p
Cap_{m}^{max}	Maximum inventory level of inventory storing m
t_{pmt}^{lag}	Time for an input to become an output of process p
f_{pm}^{V}	Volume conversion factor content m when it is processed in p
d_{pmu}	Demand of utility u per input in process p
D_m	Total demand of m

Continous Variables	
C^{tot}	Total electricity cost
F_{pmt}^{in}	Volumetric input of m to process p at t
F_{pmt}^{out}	Volumetric output of m to process p at t
I_{mt}^{lvl}	Level in inventory storing m at t
d_{ut}	The sawmills total demand of utility u at t

Binary Variables	
x_{pmt}	Indicates the start of chamber kiln batch with m in process p at t
x_{pmt}^{p}	Indicates the start of progressive kiln batch with m in process p at t
x_t^s	Indicates a change in operation conditions in the progressive kiln

The model's objective to minimise the total cost of electricity, C^{tot}, is implemented with the objective function in Equation 3.1. Where the hourly cost of electricity is determined by the hourly electricity usage, $d_{el,t}$, and the electricity spot price, p_t^{el}. x_t^s and p^s are included to limit the amount of changes of operation conditions in the progressive kiln (see section 3.1.2).

$$min\ C^{tot} = \sum_{T} d_{el,t}\ p_t^{el} + x_t^s\ p^s \tag{3.1}$$

The structure of the processes and inventories in a sawmill are identified and grouped in the model as viewed in Figure 3.1. Let the processes make up the set P. To apply different processing properties for center and side boards, choice of drying program and stage in the drying program the model has one kiln for each combination of processing properties (operation condition). The model is however constrained such that only one operation condition at a time can be applied for the progressive kiln, chamber kiln A and chamber kiln B, respectively.

The chamber kiln's operation is divided into two stages to apply different utility usages during the drying program. Stage 1 includes the heating up, capillary phase and part of the transition phase. Stage 2 includes the remaining part of the transition phase and the diffusion phase.

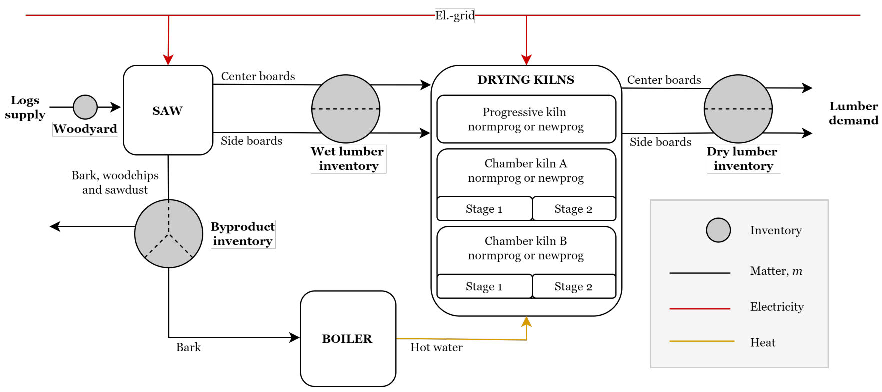


Figure 3.1: Overview of model structure.

3.1.1 Process and Inventory Capacity

All processes are constrained to operate within the bounds of their minimum and maximum capacity as in Equation 3.2.

$$\begin{cases} Cap_{pm}^{min} \leq F_{pmt}^{in} \leq Cap_{pm}^{max} & \forall m \in M,\ t \in T,\ p : t_{pm}^{lag} = 0 \in P \\ Cap_{pm}^{min} \leq \sum_{t-t_{pm}^{lag}}^{t} F_{pmt'}^{in} \leq Cap_{pm}^{max} & \forall m \in M,\ t \in T,\ p : t_{pm}^{lag} \neq 0 \in P \end{cases} \tag{3.2}$$

For the scenarios where the progressive kiln can be fed with both center and side boards the maximum capacity constraint of the progressive kiln needs to be adjusted to take into consideration that *progressive kiln center* and *progressive kiln side* are in fact the same kiln.

$$\sum_{M^b} \frac{\sum_{t-t_{pm}^{lag}}^{t} F_{pmt'}^{in}}{Cap_{pm}^{max}} \leq 1 \qquad \forall t \in T,\ p \in P^p \tag{3.3}$$

In the model the inventories are represented by the matter they are containing. Let all matters, m, make up the set M. The level in an inventory, I^{lvl}_{mt}, is limited by its maximum capacity, Cap^{max}_i, which is defined for the real inventories, I. The matters in each real inventory, M_i are thus defined as subsets to M to implement the inventory capacity constraint (Equation 3.4).

$$\sum_{M_i} I^{lvl}_{mt} \leq Cap^{max}_i \qquad \forall i \in I,\ t \in T \tag{3.4}$$

The material accumulation and flows through the inventories are balanced for each matter and time step with Equation 3.5. $F^{out}_{p'mt}$ and $F^{in}_{p''mt}$ refer to the volumetric flow from process p' to p with m as output and input respectively. Since logs are the material fed to the sawmill there is no process with it as output. The log inventory is instead balanced by an inventory input taken from a to each time step limited resource of logs, hence taking into account the limited capacity of receiving logs at the mill or a supply limit. Since there is an excess production of byproducts the inventories of these has an additional term with the possibility to reduce the level in the inventory The reduction can be interpreted as selling of byproducts however the income of such trade is not included in the model.

$$I^{lvl}_{mt} \leq F^{out}_{p'mt} - F^{in}_{pmt} + I^{lvl}_{m(t-1)} \qquad \forall m \in M,\ t \in T,\ p \in P \tag{3.5}$$

3.1.2 Process Inputs and Outputs

The material flows through each process p are balanced with Equation 3.6. f^{V}_{pm} is a conversion factor defined as the ratio of output of m per input of m', hence processes with multiple outputs has a f^{V}_{pm} of each product output. The time it takes for an input to become an output (duration of the process) is implemented with t^{lag}_{pm}.

$$F^{out}_{pmt} \leq F^{in}_{pm'(t-t^{lag}_{pm})} f^{V}_{pm} \qquad \forall p \in P,\ t \in T,\ m \in M \tag{3.6}$$

To apply that the saw can have limited operational hours, T^{saw}, the constraint in Equation 3.7 is introduced.

$$F^{in}_{saw,logs,t} \leq 0 \qquad \forall t \setminus T^{saw} \tag{3.7}$$

Inputs to the chamber kilns, P^c, are limited to be of a specific size in order for the kiln to run properly. The batch behavior and the specific batch sizes are implemented with Equation 3.8.

$$F^{in}_{pmt} = Cap^{max}_{pm}\ x_{pmt} \qquad \forall p \in P^c,\ t \in T,\ m \in M^b \tag{3.8}$$

The value of the binary variable x_{pmt} is constrained to only take the value one if a batch is permitted to started at t by Equation 3.9. Since kilns should only operate with one board type and stage at a time the premise for a batch start to be permitted is that no other batch has started within the eventually started batch's duration, i.e. t^{lag}_{pm}.

$$\sum_{M^b} \sum_{t-t^{lag}_{pm}}^{t} x_{pmt'} \leq 1 \qquad \forall t \in T,\ p \in P^c \tag{3.9}$$

Between the chamber kiln stages there are no inventories, hence are the inputs and outputs of stages related as in Equation 3.10.

$$F^{in}_{pmt} \leq F^{out}_{(p-1)mt} \qquad \forall p : p \geq 2 \in P^c,\ t \in T,\ m \in M^b \tag{3.10}$$

The progressive kiln is modeled as separate kilns for each type of lumber, since the operation of the kiln is affected by the lumber it dries. To include that these kilns are in fact the same kiln they are limited to only have one thickness as input at a time with the binary variable, x^p_{pt} (Equation 3.11 and Equation 3.12).

$$\sum_{M^b} \sum_{P^p} x^p_{pmt} \leq 1 \qquad \forall t \in T \tag{3.11}$$

$$F^{in}_{pmt} \leq \frac{Cap^{max}_{pm}}{t^{lag}_{pm}}\ x^p_{pmt} \qquad \forall t \in T,\ p \in P^p,\ m \in M \tag{3.12}$$

To favour model solutions which has few changes of operation conditions in the progressive kiln a binary variable, x^s_t, indicating this is defined and included in the objective function, Equation 3.1. The logical condition is formulated as given in Equation 3.13, where P^{p*} is P^p without p.

$$x^s_t \geq x^p_{pt} - 1 + \sum_{P^{p*}} x^p_{p*(t-1)} \qquad P^{p*} := P^p \setminus p, \forall p \in P^p, t \in T \tag{3.13}$$

3.1.3 Supply and Demand of Lumber and Utilities

The model's production is driven by a defined demand of dried lumber, $D_m t$. This is represented by Equation 3.14, where M^{bd} is the subset of matters which are dried lumber.

$$D_{mt} \leq \sum_P F^{out}_{pmt} \qquad \forall m \in M^{bd}, t \in T \tag{3.14}$$

The operation of the processes are linked to utility production and demands, d_{pmu}. d_{pmu} is negative if u is consumed and positive if it is produced. The total net consumption or production of u, d_{ut}, is determined by Equation 3.15. The utilities in U are heat and electricity.

$$d_{ut} \geq \begin{cases} \sum_{p:\ t^{lag}_{pm} \neq 0 \in P} \sum_M \sum_P \sum_{t'-t^{lag}_{pm}}^{t} F^{in}_{pmt'}\ d_{pmu}\ \frac{1}{t^{lag}_{pm}} & \forall t \in T,\ u \in U \\ \sum_{p:\ t^{lag}_{pm} = 0 \in P} \sum_M \sum_P F^{in}_{pmt}\ d_{pmu} & \forall t \in T,\ u \in U \end{cases} \tag{3.15}$$

Equation 3.15 is constrained to be larger or equal to zero for the heat utility, meaning that the heat production in the boiler needs to be larger than the consumption in the kilns.

3.2 Scenarios

The sawmills flexibility is assessed together with variations of the production procedures in the kilns. The deviations are implemented in the work as four scenarios, REF, ProgFlex, BoardFlex and FullFlex, each corresponding to some deviations from the given model formulation and/or data. REF is the reference scenario and aims to mimic the operation of a typical sawmill with the assumption that it only produces two types of boards.

The REF and ProgFlex scenarios have limited inventory capacity for dry lumber to limit the possibility for flexibility. In the ProgFlex scenario the drying could either be preformed with the normal program (normprog) implemented in the reference case or with a new program (newprog).

Newprog operates with decreased fan speed during the whole drying in the progressive kiln and only during the stage 2 in the chamber kiln. The decreased fan speed is also correlated to an increased t_{pm}^{lag}. The total electricity consumption of the programs are close to equal in the chamber kiln. The load profiles are however different, see Figur 3.2.

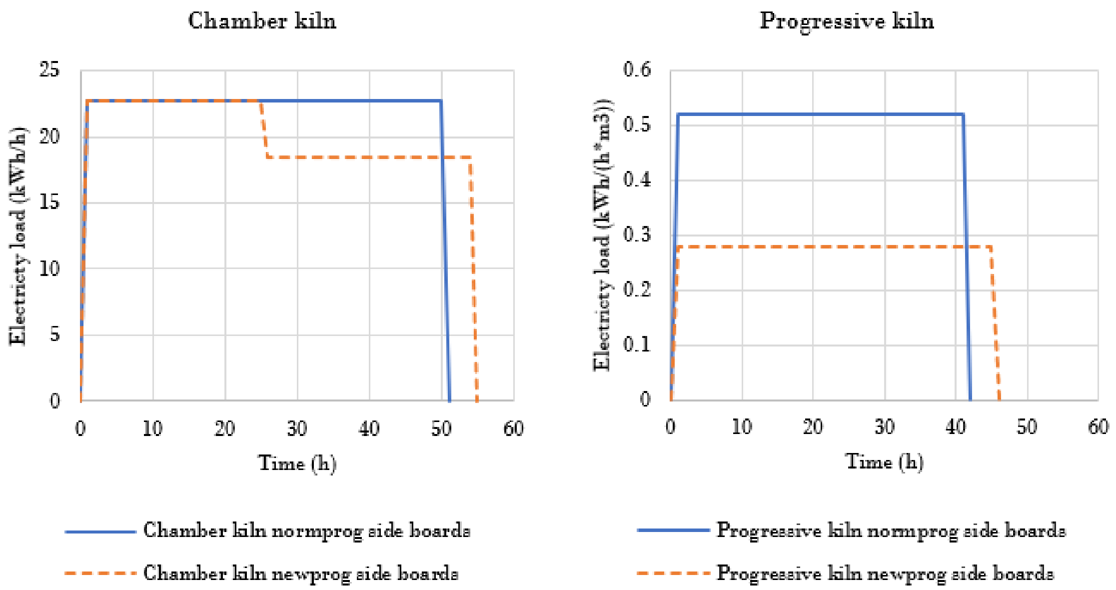


Figure 3.2: Electricity load profiles for side boards drying programs. The load profiles for center boards are similar.

In both REF and ProgFlex the operation is limited to only dry side boards in the progressive kiln and center boards in the chamber kiln. In the BoardFlex both side and center boards can be dried in any kiln and the possibility to plan the kiln operation more freely is realesed by extending the dry lumber inventory.

The FullFlex scenario aims to display the combined effects of both ProgFlex and BoardFlex, hence can all type of boards be dried with any program in in any kiln with the same capacity in the dry lumber inventory as BoardFlex.

3.3 Data and assumptions

The data which is applied to the model have been gathered from literature, measurements at Södra Wood in Värö and Unnefors, simulations and consultation with industry. Electricity spot prices are extracted from NordPool's website, and was taken for January 2022. This month is deemed to have high price variations and a generally high price level.

The chosen board types was spruce of the dimensions 41x180mm (center boards) and 25x125mm (side boards). Due to time limitations was measurements only made on a selection of the operation conditions. The data not taken from measurements was adjusted to mimic that all data had been measured and thus decrease inconsistencies. The adjustment of simulated to measured was made using the expression in Equation 3.16, where x and y indicates different board types.

$$[Adjusted\ data\ for\ x] = [Simulated\ data\ for\ x]\,\frac{[Measured\ data\ for\ y]}{[Simulated\ data\ for\ y]} \tag{3.16}$$

Other adjustments was also made for the measurements on the chamber kilns since these were made on another species and dimension. In the cases data was missing relations between boards and program types was used to extrapolate the available data. A summary of the handling and sources of parameters for the saw and kilns are presented in Table 3.2.

Table 3.2: Summary of data handling and sources

Parameter	Saw	Progressive kiln side boards normprog or newprog	Progressive kiln center boards normprog or newprog	Chamber kiln side boards normprog or newprog	Chamber kiln center boards normprog or newprog
Capacity	Assumed to cover a third of the average monthly producion of lumber in Unnefors.	Assumed to cover a third of the average monthly producion of side boards in Unnefors.	Assumed as 153% of the progressive kiln side boards.	Assumed as 81% of the chamber kiln center boards with a capacity. The capacity is evenly distributed between Chamber kiln A and B.	Assumed to cover a third of the average monthly producion of center boards in Unnefors. The capacity is evenly distributed between Chamber kiln A and B.
Electrcity demand	Litterature data (Anderson and Westerlund, 2014)	Assumed, based on the duration of each program and average fan power in the progressive kiln.	Measured for each drying program, Värö (Source of avrage fan power in the progressive kiln).	Assumed using stage duration and avrage fan power for each chamber kiln and program. Average fan power origns from measurments on pine in Unnefors.	Assumed using stage duration and avrage fan power for each chamber kiln and program. Average fan power origns from measurments on pine in Unnefors.
Heat demand	-	Adjusted simulation for normprog, which inturn was adjusted to newporg with the same relation between the programs heat demands as center boards.	Measured for each drying program, Värö.	Assumed using heat demand in progressive kiln for each program and adjusted with a factor origning from theoretical energy consumption in both chamber and progressive kilns.	Assumed using heat demand in progressive kiln for each program and adjusted with a factor origning from theoretical energy consumption in both chamber and progressive kilns.
Duration	-	Adjusted simulation for normprog, which inturn was adjusted to newporg with the same relation between the programs duration as center boards.	Measured for each drying program, Värö.	Assumed for both programs using the duration for chamber kiln center borads and a ratio between center and side boards duration in the progressive kiln.	Measured for each drying program. Measurements were made on pine and adjusted to spruce with factor calculated from simulations on both type of boards.

The inventory capacities were given from industry and are presented in Table 3.3.

Table 3.3: Inventory capacities.

Inventory	**Capacity (m3)**	
	REF & ProgFlex	BoardFlex & FullFlex
Woodyard	9167	9167
Wet lumber	2000	2000
Dry lumber	5000	500
Byproducts	15000	15000

All volume conversions were assumed to take place in the saw, meaning that the volume in the wet lumber inventory is larger in reality due to the 8 % volume decrease during the drying. The volume conversion factors that are not 1 are presented in Table 3.4. The volume conversion factors for byproducts were adjusted to take into account the unit conversion from m^3sob to m^3l.

Table 3.4: Volume conversion factors which are not 1.

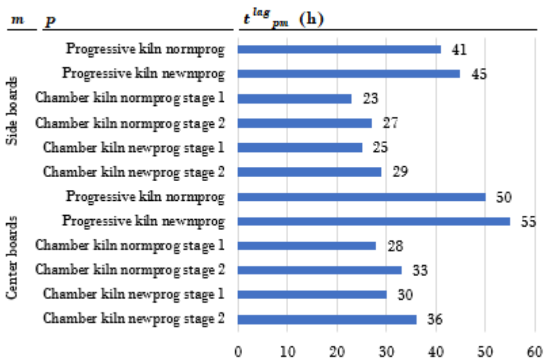
$\boldsymbol{p}$	$\boldsymbol{m}$	f^v_{pm}
Saw	Sawdust	0.25 (m^3l/(m^3sob)
	Woodchips	0.85 (m^3l/m^3sob)
	Bark	0.25 (m^3l/m^3sob)
	Lumber	0.43 (m^3/m^3sob)

3.3.1 Process duration

Process duration in the kilns was a key parameter since it was used to determine many of the other parameters. The durations for drying of center boards with normprog and newprog in the progressive kiln were measured. The durations for center boards were extrapolated to side boards with Equation 3.16 given some simulated data .

The chamber kilns duration of the stages was measured for newprog and normprog and adjusted from pine to spruce of the right dimension by a ratio between simulated drying times of each lumber type. To approximate the durations for side boards, it was assumed that the chamber kiln had the same ratio between side and center boards drying time as the progressive. All process durations are presented in Table 3.5

Table 3.5: Process durations for each process and matter. The chamber kiln A and B are identical and are thus presented together as "Chamber kiln...".



3.3.2 Lumber demand and process capacity

The demand of lumber was selected to reflect a reasonable throughput in the kilns by making it a third of the monthly average production at a real site, whereas the real site had three times the number of chamber and progressive kilns respectively. It was assumed that 70 % of the production was center boards and the rest was side boards.

The demand was used in the sizing of both the saw and kilns. By assuming a utilisation factor, C^f, of 90 % for these processes and an available production time, T^r, from 7 AM-24 PM for the saw, the process capacity could be retrieved by Equation 3.17, 3.18 and 3.19. While sizing the kilns it was assumed to only dry center boards in the chamber kiln and side boards in the progressive kilns.

$$Cap^{max}_{saw,logs} = \frac{\sum_{M^{bd}} D_m}{f^V_{saw,logs} C^f \ T^r} \tag{3.17}$$

$$\sum_{P^c} Cap^{max}_{p,center\ boards} = \frac{\sum_{P^c} t^{lag}_{p,center\ boards} D_{center\ boards}}{C^f \ T} \tag{3.18}$$

$$Cap^{max}_{progressive\ kiln,\ side\ boards} = \frac{D_{side\ boards}\ t^{lag}_{progressive\ kiln,\ side\ boards}}{C^f \ T} \tag{3.19}$$

Since boards with different dimensions take up different amount of space while they are stacked the capacities was recalculated for the opposite board type as the one used for dimensionening. The progressive kiln's capacity was increased with 53 % for center boards and the chamber kiln's capacity decreased with 19 %.

The boiler's heat capacity was determined as a third of the real site's. The heat capacity was recalculated as presented in Equation 3.20, where η_{boiler} is 0.88 which is a normal efficiency of bark boiler's. The minimum capacity was assumed to be 20 % of the maximum capacity.

$$Cap^{max}_{boiler} = \frac{[Capacity\ in\ MW_{heat}]}{[Higher\ heating\ value\ bark]\eta_{boiler}} \tag{3.20}$$

The data for the process maximum capacities are presented in Table 3.6

Table 3.6: Maximum capacities for the processes given a specific matter as input. No difference is made for newprog or normprog and chamber kiln A and chamber kiln B and their respective stages are identically sized.

$\boldsymbol{m}$	$\boldsymbol{p}$	Cap_{pm}^{max}
Logs	Saw	17.3 (m3 sob/h)
Bark	Boiler	3.2 (m3l/h)
Side boards	Progressive kiln	64 (m3/h)
	Chamber kiln	91 (m3/kiln)
Center boards	Progressive kiln	121 (m3/h)
	Chamber kiln	112 (m3/kiln)

3.3.3 Utility production and demand

The saw's specific electricity consumption was determined with Equation 3.21 and site specific numbers.

$$d_{saw,logs,el.} = \frac{[Rated\ power]\ [Annual\ operation\ hours]}{[Annual\ production]} \tag{3.21}$$

The bark boiler is assumed to operate only with bark with moisture of 55 %. The specific heat production of the boiler was calculated as presented in Equation 3.22, given η_{boiler}=0.88 and a higher heating value for bark as 0,6 MWh/m^{3}l.

$$d_{boiler,bark,heat} = -[Higher\ heating\ value\ bark]\eta_{boiler} \tag{3.22}$$

The specific electricity and heat consumption for drying of center boards with normprog and newprog in the progressive kiln were determined by measurements. From these measurements was the average fan power for the progressive kiln, $P^{fans}_{progressive\ kiln...}$ =146 kW determined. Similarly could an average fan power of in the for the chamber kiln, $P^{fans}_{chamber\ kiln...}$=24 kW be determined from the measurements. The average fan power was used as given in Equation 3.23 to approximate the the specific electricity consumption for drying of side boards in the progressive kiln and all operation conditions in the chamber kiln. In this equation the capacity of the kiln used for measurements Cap^{max*}_{pm} was used to retrieve specific values.

$$d_{pm,el} = \frac{P_p^{fans} t_{pm}^{lag}}{Cap_{pm}^{max*}} \qquad \forall p \in P^c, m \in M^b\ or\ \forall p \in P^p, m : side\ boards \in M^b \tag{3.23}$$

The heat consumption for drying of side boards with normprog in the progressive kilns was determined by adjusting results from a simulation as in Equation 3.16. This heat consumption was extrapolated to newprog using the same relation between the program's heat demands as for center boards.

The specific heat consumption in the chamber kilns stages and programs was determined by converting the data for the progressive kiln with calculated factors, f^{p2c}. These were retrieved by taking the ratio of the consumed energy in each stage of the chamber kiln and the energy consumed in the progressive kiln. The energy consumption was determined using relationships and average data from Esping (1996). The factors was 103 % for the capillary stage (1) and was 30 % for the diffusion stage (2). The chamber kilns heat consumption could thus be calculated as given in Equation 3.24.

$$d_{p,m,heat} = f_m^{p2c}\left(d_{p',m,el} + d_{p',m,heat}\right) - d_{p,m,el} \qquad \forall p \in P^c,\ p' \in P^p,\ m \in M^b \quad (3.24)$$

All utility demands which are not zero are presented in Table 3.7.

Table 3.7: Utility demand per process and matter which are not zero. Chamber kiln A and B are identical and are thus presented as "Chamber kiln...".

$\boldsymbol{m}$	$\boldsymbol{p}$	$d_{p,m,el}$ **(kWh/m3)**	$d_{p,m,heat}$ **(kWh/m3)**
Logs	Saw	23	0
Bark	Boiler	0	528
Side boards	Chamber kiln normprog stage 1	6	352
	Chamber kiln normprog stage 2	7	98
	Chamber kiln newprog stage 1	6.5	332
	Chamber kiln newprog stage 2	6.1	96
	Progressive kiln normprog	21.5	327
	Progressive kiln newprog	12.7	323
Center boards	Chamber kiln normprog stage 1	5.9	141
	Chamber kiln normprog stage 2	6.9	36
	Chamber kiln newprog stage 1	6.4	132
	Chamber kiln newprog stage 2	6	34
	Progressive kiln normprog	16.6	127
	Progressive kiln newprog	9.8	125

4

Results

This section presents the outputs from the model when it is optimised under the conditions of the described scenarios. Since the optimisation is made for the electricity cost the electricity load profiles are presented first and then followed with implications for costs, heat loads and other technical constraints.

4.1 Electricity Loads

The electricity load profiles for each scenario are presented together with the electricity spot prices in Figure 4.1. It is clear that electricity consumption is avoided during the price peak hours occurring around hour 140, 240 and 590. The highest price occurs at hour 593, the prices adjacent to this peak are on the other hand low, hence priority is given to a decrease of the load during some of the hours between hour 100-250 in all four scenarios. The scenarios REF and ProgFlex are operting at a steady load equivalent to the kilns full capacity during all other hours, while BoardFlex and FullFlex are operating with more irregular and varying loads.

In REF and ProgFlex are the progressive kilns operating at close to full availability while the load is decreased for longer periods in the BoardFlex and FullFlex. The free kiln assignment is hence shown to be enable flexibility as down ramping of the progressive kiln. The decreased utilisation of the progressive kiln leads to a increased utilisation of the chamber kiln, an effect which is clearly seen by comparing REF and BoardFlex.

The chamber kilns higher utilisation and steeper load pattern is in the scenarios BoardFlex and FullFlex used to avoid price peaks. These load decreases can be seen to occur from 1 to 12 hours which is significantly lower than the duration of the progressive kilns load decreases.

In the FullFlex and BoardFlex scenarios where the model can assign the board types to the kilns freely has the progressive kiln been changed to only dry center boards instead of side boards. Although less side boards than center boards could be fitted in the chamber kiln is the demand of of them lower meaning that less batches are needed. In the scenarios including flexible planning has this enabled to dry both side boards and center boards in the chamber kiln. When both board types are dried in the chamber kiln it can be observed that the side boards are planned to operate during the higher price hours and center boards to medium to low price hours. Furthermore, gives the increased capacity when drying center boards an effect which decreases the number of full load hours in the progressive kiln.

Figure 4.1: Electricity spot prices (SE3 January 2022) a) and Electricity load profiles in the kiln as stacked areas for scenarios REF b), ProgFlex c), BoardFlex d) and FullFlex e).

In neither FullFlex or BoardFlex are the kilns utilised to their full availability, yet are both used to dry center boards. Consequently, is the choice of kiln dependent on the electricity price and can favour both types of kilns. The specific electricity consumption for drying of center boards is higher in the chamber kilns compared to when they are dried with the new program in the progressive kiln. Meaning that when the chamber kiln is chosen above the progressive kiln, the increase electricity consumption has been countered with a decreased load during higher cost hours.

The introductions of the new programs in scenario ProgFlex and FullFlex, leads to decreased load during stage 2 in the chamber kilns and decreased load in the progressive kiln. The results, show that the new program is preferred over the normal in the progressive kiln. Although a comparison of REF and ProgFlex show that the use of it limits the possibility to decrease the load in the progressive kiln during the high cost periods. By comparing BoardFlex and FullFlex can it on the other hand be observed that the new programs favoring a higher utilisation of the progressive kiln and thus increases the possibility for strategic planning of the chamber kilns.

Regarding the choice of program in the chamber kiln is the new program not always preferred over the normal. In ProgFlex the new program is only used in one batch per kiln and both the new and normal program are used in the FullFlex scenario. In the FullFlex scenario the new programs are planned so that stage 2 occurs during the higher cost periods. The normal programs are planned in between price peaks during periods where the overall price is lower, utilising their shorter duration.

The electricity load profile for the saw is close to identical in all four scenarios. From Figure 4.2 it can be concluded that the scenarios with the possibility to dry boards in any kiln as well as have an large dry lumber storage have a slight lower number of operational hours and electricity demand. The utilisation factor of 90 % gives the possibility to avoid some high cost hours. The longest period of shut down is the a little over a day. The plot in 4.2 also reveals that the operation is strongly mismatched with the low electricity prices, since the low cost hours are during the hours of the nightly shut down.

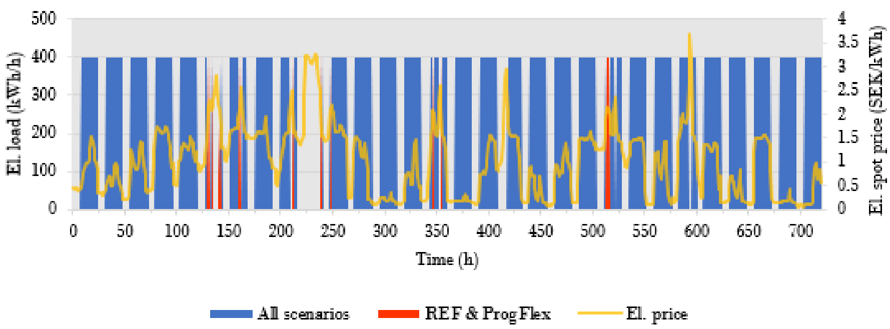
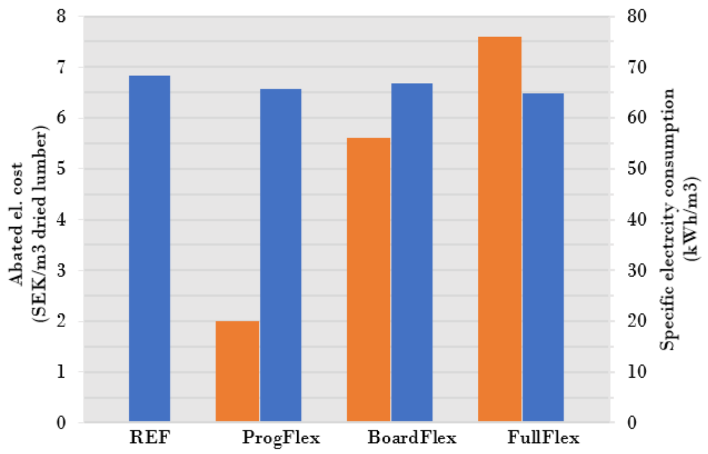


Figure 4.2: The saw's electricity load profile for all scenarios together with the electricity price.

4.2 Electricity Cost

The flexibility options results in different degrees of decreased electricity costs compared to the REF scenario which has a total cost of electricity of 240 000 SEK/month and specific cost of electricity of 72 SEK/m^3. The specific abated cost of electricity is presented together with the specific electricity consumption in Figure 4.3. The specific electricity consumption of all scenarios is slightly decreased compared to the reference scenario. The results are only comparable with the specific numbers since the scenarios resulted in different amounts of produced lumber.



	REF	ProgFlex	BoardFlex	FullFlex
Abated el. cost (SEK/m3 dried lumber)	0.0	2.0	5.6	7.6
Abated el. cost compared to the total cost of el. REF	0.0%	2.8%	7.8%	10.6%
Specific electrcity consumption (kWh/m3)	68	66	67	65

Figure 4.3: Specific consumption of electricity together with the abated cost of electricity and the corresponding share of the specific cost in the reference scenario.

The decreased cost for electricity can either stem from decreased electricity consumption or the movement of loads from higher to lower cost hours. The results indicate that the introduction of new programs in ProgFlex leads to a decreased electricity consumption, and the possibility to dry boards in any kiln in BoardFlex increases the possibility to operate during low cost hours. This is also confirmed in the load profiles in Figure 4.1, where the load profiles ProgFlex are similar to REF but on lower level. BoardFlex has a load of the same magnitude as REF when the progressive kiln is not ramped down. However has the increased kiln availability enabled a decreased load in the progressive kiln during longer (about 100h) high cost periods as well as avoidance of chamber kilns operation during peak hours.

The FullFlex scenario combines the effects of ProgFlex and BoardFlex. Since the specific abated electricity cost of the FullFlex scenario is the same as BoardFlex and ProgrFlex added together, it can be concluded that the effects are neither mitigating or amplifying each other.

In the diagrams in Figure 4.4 are the hourly load sorted according to the price duration curves, it is clear that the cost reductions stems from different types of measures in the production. It is confirmed that the cost reduction in the ProgFlex scenario stems from a decreased load and not from avoidance of the high cost electricity. In contrast has the loads been displaced from the high cost periods to lower cost periods in the scenarios with flexible planning.

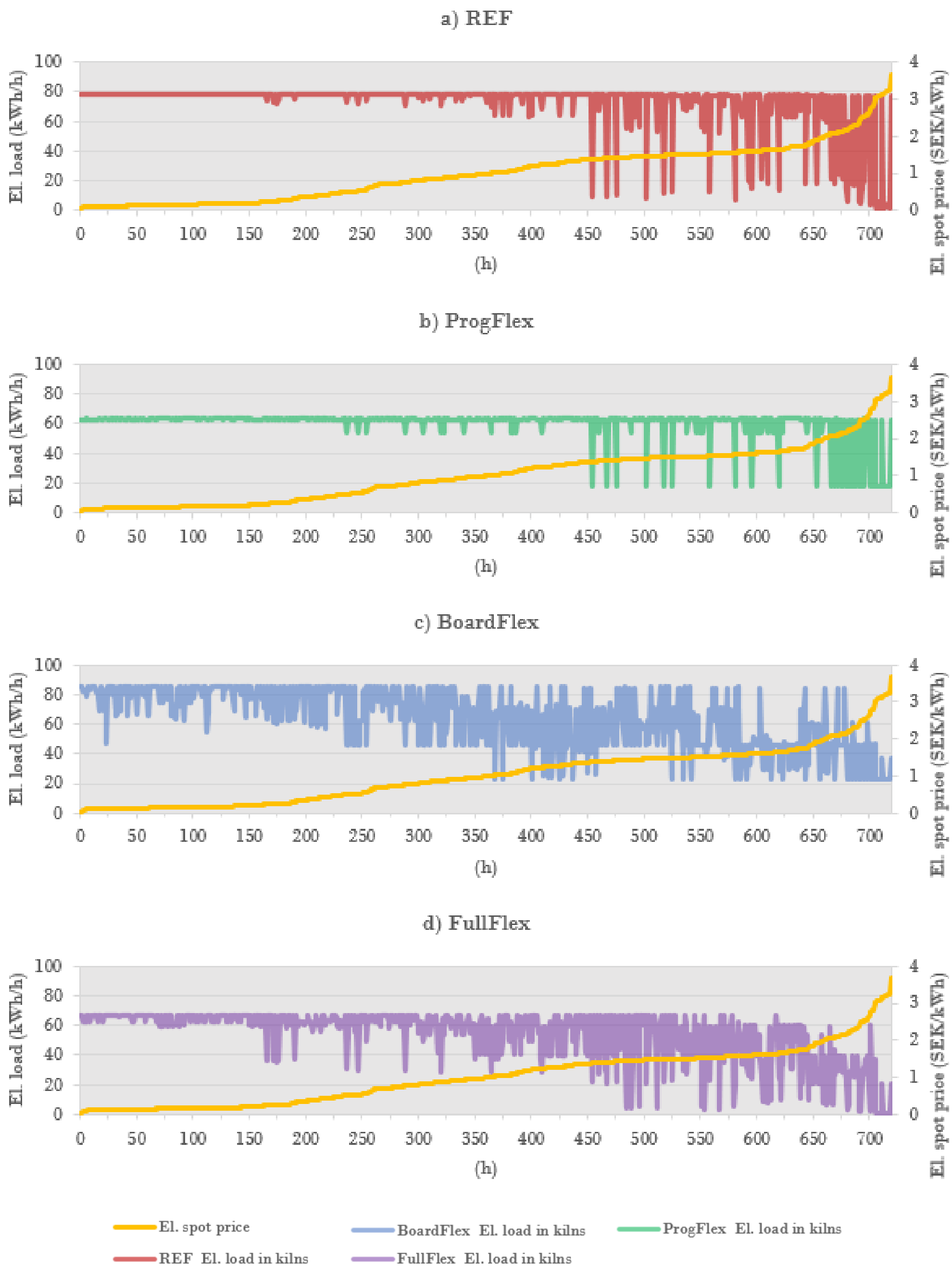


Figure 4.4: Price duration curves with corresponding electricity loads in the kilns for each scenario (a)REF, b)ProgFlex, c)ProgFlex and d)FullFlex).

What is interesting is that the load is not shifted from the highest cost hours but rather from the hours with relatively high cost 1.5-3 SEK/kWh to lower cost hours. This is a result of running the REF scenario as a cost optimisation since the operation during the highest cost hours has already been avoided to a large extent.

Moreover, it can be observed that the BoardFlex and FullFlex scenarios have a decreasing trend with irregularities distributed over all electricity prices. In contrast to REF and ProgFlex which have a more even distribution with increasing irregularities as the electricity price is increased. This comparison shows that the avoidance of high cost hours with flexible planning entails the avoidance of more low cost hours.

Regarding the magnitude of the loads it can be observed that the scenarios with new programs leads to a reduction of approximate 20 kWh/h throughout the whole period. The BoardFlex scenario has a decreased load of approximate 30 kWh/h distributed around the median price. The load is however increased at the hours with prices above 2 SEK/kWh with approximate 20 kWh/h. In the FullFlex scenario are the increased load during this high cost period displaced to hours with a price around 1 SEK/kWh.

4.3 Heat Loads

The kilns heat loads corresponds to the boiler operation, viewed in Figure 4.6. The stages of the program in the chamber kiln have a notable difference in heat demand, causing large variations in boiler load in the REF scenario, already. The ProgFlex scenario follows the same variation pattern as REF. BoardFlex and FullFlex scenarios have variations of the same magnitude, but more irregular.

The boiler is assumed to have bark as its only fuel, hence is the heat consumption proportional to the bark consumption. The scenario's differences in boiler load profiles has not had a significant impact on the specific consumption of bark (see Figure 4.5). A slight increase from REF and ProgFlex can be observed in the BoardFlex and FullFlex scenarios.

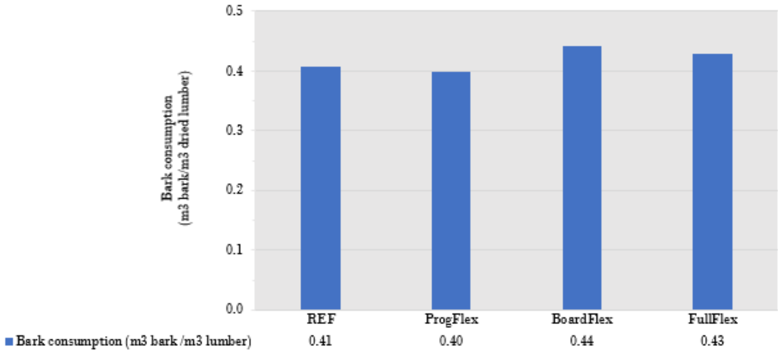


Figure 4.5: Specific consumption of bark for each scenario.

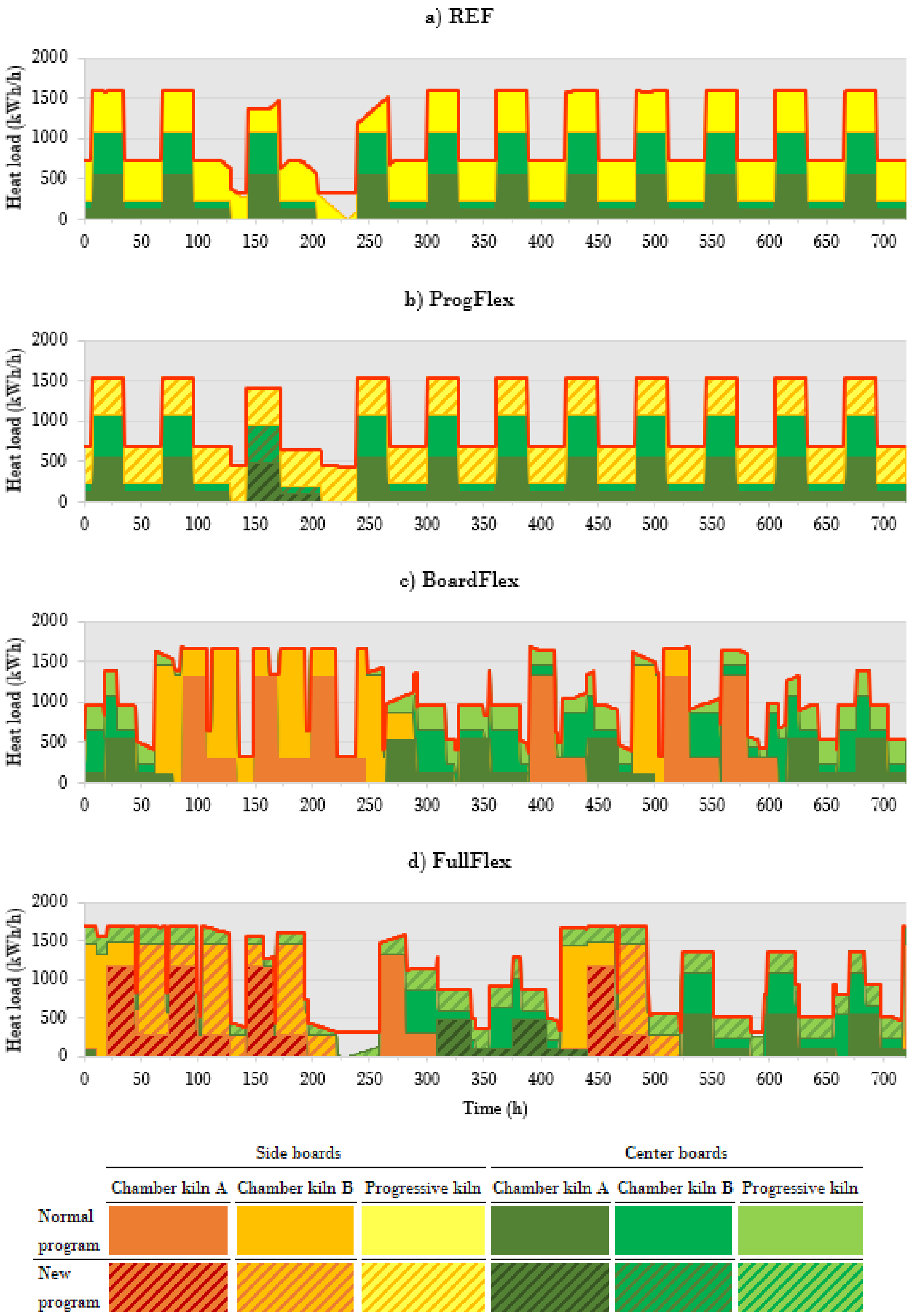


Figure 4.6: Heat load profiles in the kilns as stacked areas together with boiler load as red line for scenarios REF a), ProgFlex b), BoardFlex c) and FullFlex d).

4.4 Technical & Logistical Constraints

Inherent properties which are constraining the operation are to a high degree implemented in the model formulation. Some results are however important to examine to see implications from the flexible operation on lumber quality and how the inventories are utilised.

4.4.1 Kiln Operation Distribution

The changes in kiln operation can have implications on the product quality. Thereof, the distribution of lumber dried in each program and kiln type is presented as the production procedure distribution for all scenarios in Figure 4.7.

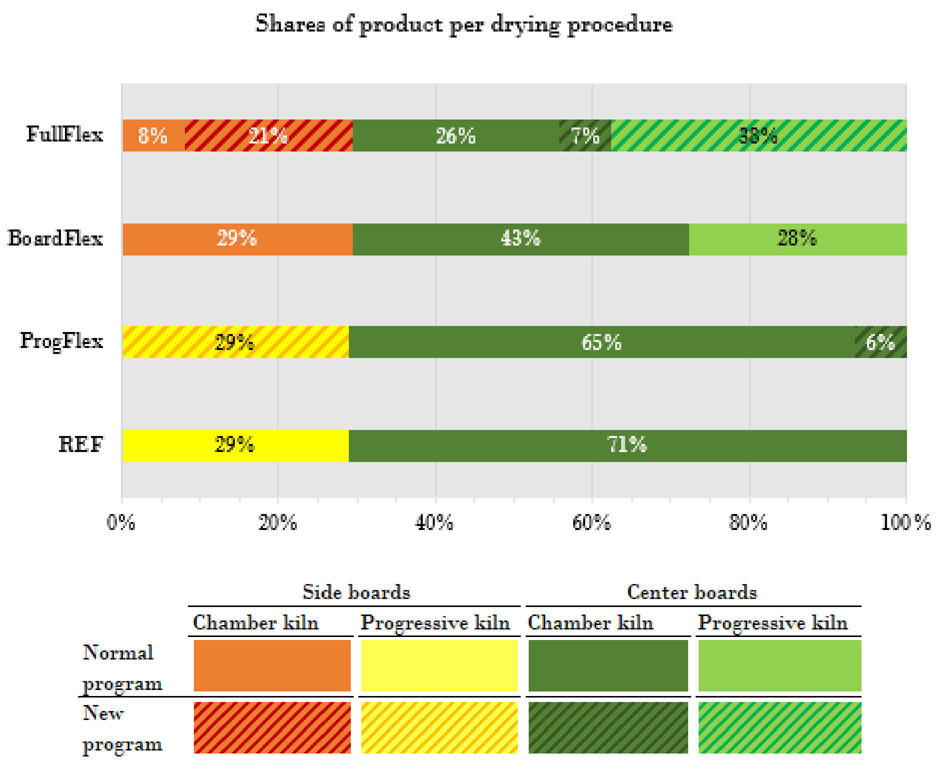


Figure 4.7: The scenario's resulting throughput for each lumber type and drying procedure, distinguishing between both programs and kilns.

The selection of kiln type is predetermined in the REF and ProgFlex scenarios giving them approximately same distribution as the ratio between center and side boards. In the BoardFlex and FullFlex scenario the shares can be altered. In the BoardFlex scenario the boards which are dried in the progressive kiln are changed from side boards to center boards but still kept on the same level as in ProgFlex and REF. In the FullFlex scenario the share which is dried in the progressive kiln is increased by about 10 %-points to 38%.

4.4.2 Inventory Capacity

The utilisation of the inventories are central for the flexible operation examined in this project. To fulfill the lumber demand each hour it either has to be an output from the kiln of at least the same size or the level in the inventory needs to compensate for any differences. Hence to have pauses in the operation of the kilns the inventory level needs to be larger than the demand during the pause.

The utilisation of both the dry and wet lumber inventory is presented for each scenario in Figure 4.8. The zig-zag profile of the inventory is a result of the batch operation of the chamber kiln and the nightly shut downs of the saw.

The inventory level never reaches the maximum capacity in any of the scenarios but instead is the flexibility limited by the capacity in the kilns. In the REF and ProgFlex scenario, where the boards can only be dried in one type of kilns, the inventory level is slowly increased from hour 300 to 100 (considering the 700th hour being connected to the 0th). In the presented load curves (Figure 4.1 and 4.6) it can be seen that the chamber kilns are operating at its full capacity during this period, hence this is the maximum pace in which the inventory level can be increased in these scenarios.

In the BoardFlex and FullFlex scenario more kiln capacity is available as the boards are not assigned to a specific kiln. This is caused by the kiln capacity difference between side boards and center boards. The result of the increased capacity in the kilns, is clearly more room for flexible operation. The effect of this can be seen as an increased maximum level of the inventory and in the load profiles as drying of the boards can be limited to one type of boards during the periods.

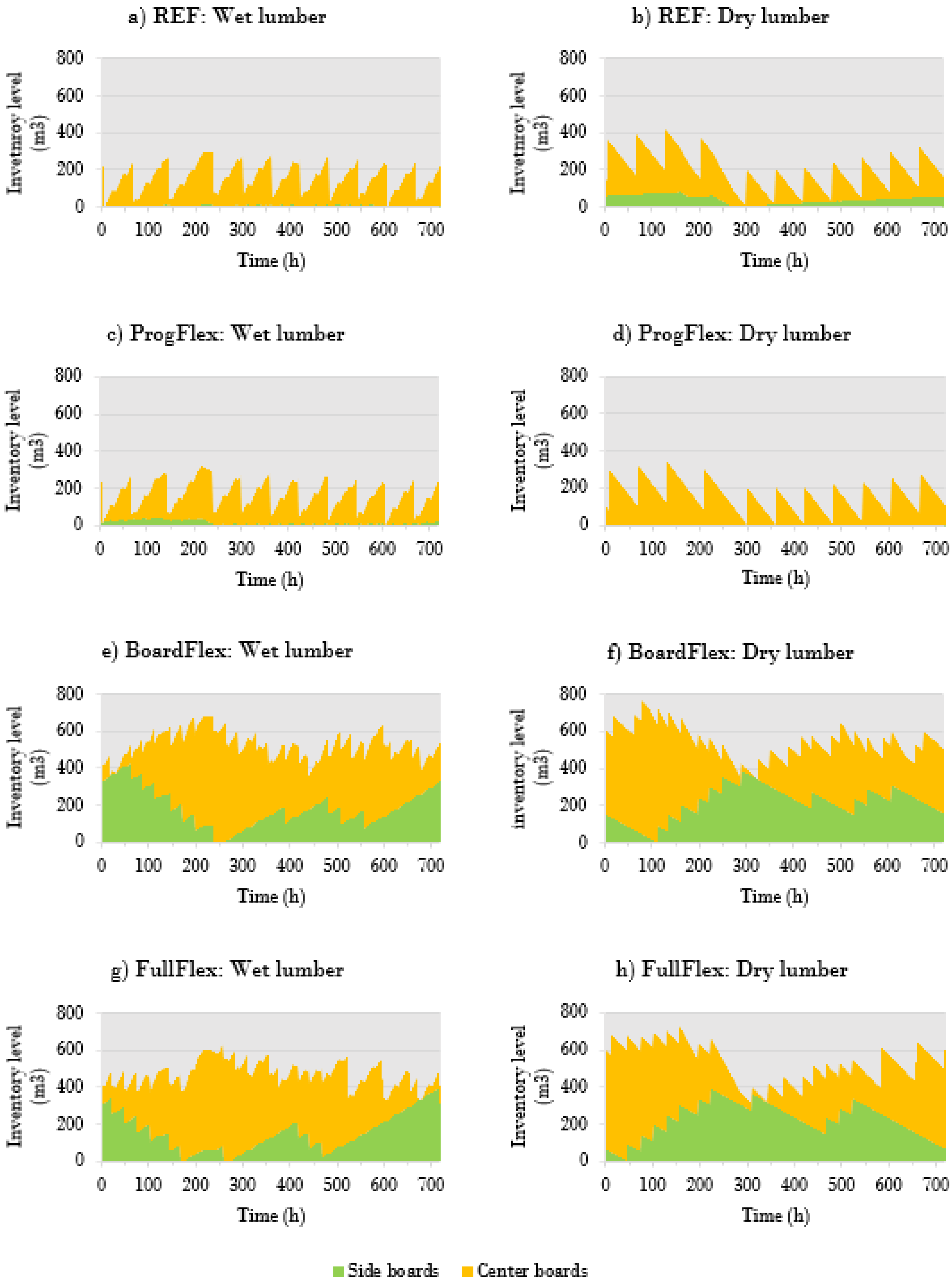


Figure 4.8: Inventory level of dry and wet lumber inventories for scenarios, REF a) and b), ProgFlex c) and d), BoardFlex e) and f) and FullFlex g) and h).

5

Discussion

This section discusses how the assumptions and model limitations impacts the results and the real potential for flexibility.

5.1 Method Limitations & Assumptions

Firstly, one should be cautious about interpreting the results of this study as the scenario with the lowest cost or largest amount of flexibility is the optimal since the optimisation is only taking the electricity price into consideration. The effect of this is that the model prioritises a solution with a small electricity price reduction with the expense of a possibly larger loss in lumber quality, heating fuel efficiency or time efficiency.

The assumption that the sawmill only produces two types of boards is a crude, yet made as a simplification to avoid too heavy computational effort where the presented model has rather long computational times. The results could however be extrapolated with caution to more board types if the dimensions of center and side boards are regarded as representations of boards with more or less energy demanding drying procedures, respectively.

The model is given perfect foresight of the electricity prices, meaning that the planning of operation in the model is better with respect to the months electricity prices than what is possible to achieve in reality. In reality the kiln operator or planner only has access to actual prices for the next coming day and possibly a forecast of electricity prices for a few more. Thus, is the possibility to start or ramp down drying strategically more limited, especially when considering that the processes have a durations for several days.

Perfect foresight in combination with the limited product catalogue and the connection between the start and end time are in addition contributing to an overestimation of the inventory availability. These artefacts causes the inventory levels to be increased to a level which is required to cover the demands during the high cost periods where the level is at least one time point decreased to zero. With limited foresight in reality, will the inventory level likely not be perfectly planned as in the case of this study. Consequently, a buffer stock of products would be needed to meet demand at all times. However, will the decrease of inventory capacity probably not be large enough to make the maximum inventory utilisation of approximate 10 % limiting for the flexibility.

The connection between the start and end point causes the inventory levels, production and demand to be in balance over the month. If the model is optimised for a longer period, e.g. a whole year it is possible that other limitations and seasonal patterns for the inventory utilisation could be revealed. For seasonal storage could a larger inventory capacity be needed and in light of the above implications that the in this study assumed capacity could be over estimated is it not unlikely that the inventory could be restricting in such scenarios.

The change of boards which are dried in the progressive kiln is a finding which should be regarded with caution, although it is the most electricity efficient way of assigning the boards. The reason for that is the correlation to negative effects on the productivity and other costs. Specifically, are the results in Figure 4.5 showing that this solution is less fuel efficient. Moreover, the change from chamber to progressive kiln is related to a negative impact on the product quality control (H. Johansson, personal communication, May 25, 2022).

The relation between the kiln capacities for side boards and center boards is in addition affected by inconsistencies stemming from differences in the package sizes at Värö and Unnefors. The inconsistency causes the capacity in the chamber kilns to be overdimensioned when it is operating with side boards. Since kiln capacity has emerged as an important factor with regards to the potential for flexibility, is some of the released flexibility in the scenarios BoardFlex and FullFlex stemming from this data error. To see the potential for flexibility caused by flexible planning solely the model should be run with a new and consistent data set.

Another production feature which has been excluded from the model is the time for loading of the chamber kilns which is about an hour (Vanzetti et al., 2021). If these would have been included one could expect a larger variation in the loads since the chamber kiln loads would go down to zero for at least an hour between each batch. On one hand, it is not likely that this would have an effect on the choice of program or which boards the chamber kilns are operated with. On the other hand the planning could be affected since it could be beneficial to plan the reduced electricity load at peak price hours, similarly to the planned gaps in between batches in the end of the FullFlex scenario.

Considering, the gathered data which is taken from several sources and although an attempt of adjusting it to be similar to the measured the inherent uncertainty that this comes with is possibly not insignificant. The data for a specific sawmills can e.g. have kilns another order of magnitude with regards to total and instantaneous electricity demands or a distribution of the kiln capacity that differ, this can both result in an increased or decreased potential for flexibility compared to this study.

The electricity prices in January 2022 are deemed to be both high and have high volatility within the days compared to historical data. It is likely that the price will develop in this direction although price profiles for other months can result in a different matching of specific load reductions. The general findings regarding which kiln or program to match with a certain type of variations would however persist.

The energy loads in the progressive kiln is in this study ramped up and down proportional to the amount of lumber currently in the kiln. Although it is possible to decrease the load in events of shut down or start up are the electricity load profiles usually step functions while the representation of the heat loads are more realistic. This means that the real flexibility for the operation of the progressive kilns load is lower than the given by the results in this study.

Furthermore, could the model's optimal operation plan be biased from assumption of the cost for changing operation procedure in the progressive kiln, p^s. The real cost and quality risk that a change in operation procedure is correlated to is unknown. If the cost has been assumed at a too high level, the flexibility opportunities a change could provide are wrongly excluded.

5.2 Development of Sawmill Operation and Planning

This study raises intriguing questions regarding ways to use the kiln's capacity more efficiently since this emerged as the main constrain for the flexible operation. The study reveals that changing the progressive kiln to dry center boards and the chamber kiln to dry side boards instead of side boards is one way of doing so.

The cost reduction of these planning or operation procedures could however be mitigated by increases in other expenses such as higher fuel usage or loss of lumber production. Thus, the cost reductions should be compared with the potential increased expenditures related to the flexibility measures to see during what circumstances it leads to profitability. The determination of such a tipping-point is highly interesting for further research.

The results of this study reveals that the operation of the saw is highly mismatched with the electricity prices. In addition are they implying that operation during the night could lead to decreased electricity costs. Such a change could however be correlated to an increased cost for salaries which would mitigate or possibly eliminate the benefit. Additionally, changes of the working schedules are usually precarious questions, since they are connected to work environment and labour law. Otherwise the saw is limited due to the high degree of utilisation and the one sided operation.

5.3 Interaction with the Electricity System

The operation has in this study been optimised with regards to the objective of minimising the costs of electricity at the sawmill. Nevertheless are interest of the sawmill inline with the interest of using the sawmills as flexibility providers to the electricity system. The results of this study shows that it is possible to move load from high price hours to hours with lower prices as well as to plan the production which decreases the total electricity consumption at the mill.

The planning of the batch kiln decrease the load during short periods when there are short peaks in electricity prices (see e.g. FullFlex scenario hour 593). This implies that strategic planning of these kilns can contribute to shaving of peaks in the electricity systems load. Moreover, the planning of the progressive kiln can contribute with load reductions during longer periods which with regards to the electricity system contributes to smoothing of long term variations in the electricity load and prices.

The results are showing that the flexible electricity loads are on a small magnitude (around 20 kWh/h, see Figure 4.4) compared to the total load of the Swedish electricity system, and the significance of a single mill in the larger system is very small. Nevertheless, are the wood industry in Sweden having hundreds of kilns in Sweden, thus could the flexible operation of the aggregated load have a significant impact. There is also a possibility that a single mill could be a contributor to solving issues occurring more local level of the electricity system despite it’s low capacities.

The implementation of flexibility which has a significant impact on the electricity prices and system loads are however tricky to implement with only market forces since the value of the flexibility and thus the incentive for it is devalued as the system loads are smoothened. Policies or flexibility markets could be one way forward and this study has shown that the sawmill’s could have an active role within them.

6 Conclusion

The study has successfully represented the sawmills production procedures with a MILP model. Inconsistencies in data are impacting the results with regards to kiln capacity, yet operation procedures which are decreasing the cost of electricity and flexibility services to the electricity system are identified.

The load in the saw is the largest electricity load and is in this study 400 kWh/h, this load is however shown to be limited to operate flexibly since it is a main process with high utilisation factor. The flexibility could however be increased with the discussed night shifts.

The kiln capacity is found to be the limiting factor for the duration of the load reductions. A change in kiln assignment, assigning the center boards to the progressive kiln emerged as one way to increase the total kiln capacity. Additionally, is the inventory capacity is not shown to be limiting where the maximum utilisation of the capacity was only 10 %.

Flexible operation with newprog are preferred in all scenarios for the progressive kiln whilst only being selected in the chamber kiln when the electricity price profile has a suitable pattern. The profound consequence of the introduction of newprog is that it results in a decreased electricity load. The merit from this is however needed to be weighted against the decreased productivity.

The scenarios with flexible planning reveals that long high cost periods can be managed by ramping down of the progressive kiln and short peaks in electricity prices can be managed by delaying the start of chamber kilns.

To estimate the total value of making use of the flexibility shown in this study the model should be complemented with the entire cost structure of all production processes, as well as the values created. The present study is limited to minimization of electricity costs.

Considering the effects on the electricity system it is revealed that the flexible loads are small compared to the demand on the electricity market. Still, if all sawmill respond to electricity market signals the aggregate effect may contribute with flexibility significant to the electricity generation system.

7
Future work

The findings and uncertainties of this study has brought light to further research which should be undertaken to confirm the viability and impact of the results as well as investigate other potential flexibility options. Research questions that could be asked include:

- Can the loading of the chamber kilns be planned at strategic time points to avoid peak prices? How would the inclusion of the chamber kiln loading affect the findings of this study?
- Can the in this study found potentials for electricity price reductions be motivated to implement given the total cost structure of lumber production?
- Can it be profitable to operate the saw during nights and do maintenance during peak hours?
- Can the kiln capacity be extended in any other way than changing kiln assignment of the boards? Would it be worth to invest in over capacity to be able to operate more flexibly?
- Can flexible planning of Sawmills be used as a strategy to meet seasonal variations and would that lead to inventories being limiting rather than kiln capacity?
- Can productivity losses be included in the model?

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