Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Miguel Las Heras Hernández

System Analysis of a Multi-Plant Sawmill Company.

Application to inform logistics.

Master's thesis in Industrial Ecology
Supervisor: Daniel Beat Müller
Co-supervisor: Chipo Sitotombe, Pasi Aalto
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Kunnskap for en bedre verden

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ABSTRACT

The current level of system understanding about the sawmill industry in central Norway requires an improvement to allow a robust assessment of the forestry industry in the region, which is required for the bioeconomy-boosting initiatives of Trøndelag fylkeskommune. Previous studies of the sawmill industry consider it as a single plant process, limited to the primary sawing of roundwood. This thesis performs a Material Flow Analysis of the production in Inntre Kjeldstad, a multi-plant sawmill company in the Trøndelag region. This allows quantifying the mass of wood used by each plant at every stage of the production, delivering a full picture of the flows of material in the company visualized in a Sankey diagram. Especial focus is placed on the interconnections between plants through internal trade, quantifying the use of transport (in tonne-kilometre) and the CO_2 emissions associated: 15% of the mass of semi-finished products is transported to supply other plant's production and 22% of the mass of post-processed products is transported between plants before being shipped to the end customers. This use of road transport causes the emission of 278 tonnes of CO_2.

The detailed definition of the production highlighted the importance of accurately depicting the processing to achieve a proper consideration of the production limitations and a higher level of detail on by-products generation. The simulation of reducing the use of transport yielded that a 33% reduction of transport use and emissions would be achievable by reducing redundant routes (*double flows*) and changing the purchasing patterns of the company, but this would require a re-assessment of the company storage and re distribution of the production according to their geographical location.

INFEED
Photo by Miguel Las Heras

ACKNOWLEDGEMENTS

First of all, I would like to express my huge thanks to Daniel Beat Müller for conveying so much enthusiasm about this topic and the MFA in general. Also, thanks to Chipo Sitotombe for such an amazing collaboration (and great road trips to visit the plants hehe). And, of course, thanks to Pasi Aalto for his brilliant vision, for facilitating the contact with the company, and most of all for making this project so much more joyful.

This thesis would not have come to fruition without the invaluable collaboration of Rolf Solberg, General Manager of Kjeldstad Trelast AS, the time and effort dedicated by all the plant managers, providing vital insights for the project. Huge thanks to them all and the company for agreeing to collaborate on this work.

SAWDUST

Photo by Miguel Las Heras

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1. INTRODUCTION

1.1. Motivation

Trøndelag region efforts to organise the industry and its utilisation of resources optimally and sustainably require knowledge of their current use and distribution. Wood is one of the main natural resources (Fylkesmannen i Trøndelag, 2019) and also comes with a high potential in terms of sustainable economies and climate change mitigation, which is promoting its use. Therefore, an analysis of the wood processing industries is needed. Among these industries, sawmills are the second most relevant one in the region, but still understudied (SSB, n.d.-e).

In order to contribute to this understanding, this thesis analyses the flow of wood through Inntre Kjeldstad, one of the main sawmill companies in Trøndelag (proff.no, n.d.). It is composed of several plants spread over the region. The internal linkages between plants and processes are studied, and the focus is placed on understanding how the system works at a company level.

The study is also used as a tool for the company to analyse its internal transport patterns, e.g. the flow of goods between the plants, and analyse the impacts of implementing potential transport-reducing strategies.

1.2. Background

1.2.1. WOOD

The volume of roundwood removals for industrial use in the European Union has been on a steady increase for the last 20 years, peaking in 2019 with 384M m^3 out of which, 303M m^3 were coniferous. Norway extraction follows a similar trend, peaking at 11M m^3. Roundwood in Norway is primarily utilized in industrial applications, dedicating only 5% to fuelwood that remains stable. This is a total opposite trend to the European average, where the utilization of roundwood as fuelwood has been increasing over a 6% since 2000, reaching a 23% in (European Commission. Statistical Office of the European Union., 2020).

Within Norway, the Hedmark region fells roughly a third of the total country extractions. The Trøndelag region extracts 5% of the total and 9% of the spruce.

2019. In 2019, 57% of the Norwegian roundwood extraction was used as sawlogs. In the Trøndelag region, this ratio is lower, where only 47% are sawlogs due to the higher relevance of the pulpwood industry that uses 53% of the felling. This utilization of forestry resources is supported by an increasing growing stock, steadily incrementing around 3,4% for the last 70 years and slowing down to 2,5% during the last decade (SSB, n.d.-e). The stock of roundwood in Trøndelag has doubled since 1920 and has still potential to increase. However, climate change places a risk on this availability due to milder winters that would difficult its accessibility and extraction (Fylkesmannen i Trøndelag, 2019).

1.2.2. BUILDING MATERIALS

Wood industries have a high representativity in the Norwegian economy, being the 4th group within Wholesale trade, only 3 percentual points below "Wholesale trade services of fish, crustaceans and molluscs" (SSB, n.d.-b).

Even though there are regions in Norway with a higher forestry activity, Trøndelag is placed as one of the northern regions with sawmill and pulp mill activities, making it the main supplier for the regions in the North (Landbruks- og matdepartementet, 2015).

The importance of wood as a resource also falls on its importance for Climate Change mitigation. The use of wood as a construction material is on the rise (FAO, n.d.), and it is expected to keep up with that trend thanks to its superior technical properties and ecological advantages such as low carbon intensity (Hildebrandt et al., 2017). Wooden products in buildings act as a sink for CO_2 with potential to store up to 310 CO_2kg m−2, which under certain scenarios could capture an amount of carbon equivalent to 47% of the European cement production in 2018 (Amiri et al., 2020) and coupled with recovery of residues to use them as an energy source, substituting fossil fuels, lowers even more energy and CO_2 balances (Gustavsson & Sathre, 2006; Werner et al., 2005). Wood construction products also provide a preferable alternative to traditional fuel-based products as a lightweight solution to high load-bearing, increasing the material efficiency (Hafner & Schäfer, 2018; Hertwich et al., 2019).

Norwegian building stock is increasing (SSB, n.d.-a), and so it is the expected consumption of construction materials. Considering Norwegian environmental strategy and its interest to encourage the use of wood as a construction material, not only for single-family houses but also to extend it to bigger applications (Landbruks- og matdepartementet, 2017; Statsbygg, 2013), higher demand for sawn wood and engineered wood materials can also be expected.

1.2.3. TRANSPORT

While the European Union has committed to reducing GHG emissions and aims for net-zero emissions by 2050, transport emissions have increased by a 23% since 1990 and road transport emissions have grown by almost 27% (EEA, n.d.-a; Enzmann & Ringel, 2020). Similarly, the road transport emissions in Norway 13%, primarily due to freight transport, in form of emissions from vans heavier vehicles. The emissions due to road transport of goods have increased almost a 60% since 1990, and the amount of tonne-kilometres transported keeps increasing (Norwegian Environment Agency, n.d.). Norwegian efforts on road freight transport emission reductions are focused on decarbonising routes over 300 km (Klima- og miljødepartementet, n.d.).

Norwegian GHG emissions from the building sector account for 15% of the total national emissions and 10% of them is solely originated by transport of the building material. Also, costs of transport are declared as one of the challenges for the forestry and wood processing sectors in Norway (Landbruks- og matdepartementet, 2015).

1.3. Existing research

1.3.1. SAWMILL INDUSTRY

Research concerning sawmill industries is mostly approached from the Agricultural and Material science areas. The focus of study starts at the beginning of the supply chain, the forestry management (Baskent & Keles, 2005). Since it is shared with other wood processing industries such as pulp and paper, panels and energy processing, presents a high potential to be improved by integrating all of them, but faces the challenge of obtaining data from the business system (Carlsson & Rönnqvist, 2005). However, even though the supply chains of these industries are highly associated and present a challenge for the industry, there is a lack of work towards integrating them and build a systemic understanding of the linkages between them (D'Amours et al., 2008; Toppinen & Kuuluvainen, 2010).

Roundwood, the main raw material of the sawmill industry has also been deeply analysed. It is one of the variables that creates the most uncertainty in the sawmill production due to its bark content, and non-homogeneous qualities (Zanjani et al., 2011). Hence, gathering relevant information about the material from the early stages, even in its standing tree form, would improve the planning (Oja et al., 2004; Uusitalo, 1997). To solve this uncertainty right before production, systems such as fast scanning system are in place (Chiorescu & Grönlund, 2004; Han & Birkeland, 1992; Wagner et al., 1989), but it is not until debarked when the most accurate scaling of the roundwood before sawing can be made (Gjerdrum, 2012).

At the plant level, the study of sawmills focuses on improving logistics and planning and optimizing the sawing process. Models are created to help match production and demand, balancing out such a highly variable yield setting (Alvarez & Vera, 2014; Kazemi Zanjani et al., 2010; Maturana et al., 2010). Also, to cope with the variabilities of supply and demand, inventory management strategies are suggested (Gronalt & Rauch, 2008; Shahi & Pulkki, 2015; Silver & Zufferey, 2005). The optimization of sawing processes is mostly undertaken by models that improve the decision taking of cutting patterns (Hinostroza et al., 2013; Vergara et al., 2015). A more comprehensive analysis and description of a sawmill plant and its functioning can be found in Walker & Walker (2006) book, which thoroughly describes the whole primary processing of wood, although this work does not focus on the sequentially of the processes.

Provided the intensive by-product generation of the sawmill operations, the potential applications of these resources are also an important area of research. Sawing by-products can become bioenergy resources as pellets and briquettes (Cesprini et al., 2021; Wolf et al., 2006), or as second-generation biofuels through gasification (Kravanja et al., 2012; Swain et al., 2011). Also, production of chemicals and textiles (Hurmekoski et al., 2018), or fish feed (Solberg et al., 2021). This broad market of applications for sawmill by-products has indeed triggered studies on the potential competition that these new uses could place on the supply of raw materials (Packalen et al., 2017). However, several assessments evidence the potential symbiosis between them and the sawmill boosting each other's production (Bryngemark, 2019; Pätäri, 2010; Wan et al., 2012). Nevertheless, even though sawmills might benefit from the entry of new actors in the market, it could be detrimental for other industries that are also linked to them, with a negative impact or by limiting potential benefits. There are not many studies focusing on the interactions between wood processing industries within a region or within a company(Kong et al., 2012). One of them studies the viability of a symbiosis of forestry industries and although it concludes that it would yield financial benefits, it also points out the difficulties of extrapolating such model to other scenarios (Karlsson & Wolf, 2008).

While sawmills are not excluded from research, this is concentrated on certain specific areas of the production. There is little research about the internal organization of sawmills, the variety of production lines to achieve different productions and their differences in recovery rates and by-product generation. A study of cooperation between plants showed the great potential of a collaborative optimization approach, where 11 plants plan their production as a co-operative instead of limiting to individual optimization. Its conclusion suggests that a 15% increased profit is achievable (Singer & Donoso, 2007). This study also sets an interesting classification of the production steps that go beyond the approach common to the majority of papers where the whole production is aggregated. It divides the processes into 2 main transformation stages, and 2 storages. The first transformation groups the production until sawing, and the second includes drying and post-processing. The storages, placed after each transformation process, are defined as raw and dry products (semi-finished and finished) that can be traded between the members of the co-operative.

1.3.2. MODELLING…

...wood use

In addition to the already mentioned models that study supply chains of several forestry industries (Karlsson & Wolf, 2008; Kong et al., 2012), some other models use Material flow analysis to trace flows of wood to assess the potential use of by-products as sources of energy and identify risks in the supply (Ackom et al., 2010; Ghani et al., 2014). None of these studies focuses their attention on the sawmill industry in particular, neither on the production of engineered wood products. Especial attention deserves the study carried out by Tellnes et al., 2011 that quantifies the flow of wood and its by-products through the Norwegian sawmill, and separates several transformation processes performed on the products before drying.

MFA has been previously used to model the whole supply chain of forestry at national levels (Gonçalves et al., 2021; Lenglet et al., 2017; Zheng, 2013), but there is a lack of research in smaller regions, which is a common weakness to this methodology (Huang et al., 2007). Even less common is its use at the company level, even though it would be an equally valid tool with the potential to map the flow of production and find material losses (Diener et al., 2013; Wang & Milis, 2018).

...use of transport

MFA methodology usually approaches transport in a system by defining it as a process, which allows quantifying its costs or emissions (Brunner & Rechberger, 2016). An analysis of the flows of materials and energy through the iron and steel sector in the UK quantifies the use of transport as exergy consumption, depending on the transported mass, distance and means of transportation (t*km*MJ) (Michaelis & Jackson, 2000). A study in Vienna linked material and energy efficiency by quantifying the use of transport in terms of “mobility service and stocks”, indicated by person*km travelled and the number of trips conducted (Virág et al., 2021). The most direct way of quantifying transport in an MFA system is found in the work of Font Vivanco et al., 2012, where Transport Intensity is defined as the ratio of kilometres that certain quantity of material flow is transported during a given timeframe.

...interactions between the actors of a company

A review of several strategies for coordinated planning in multi-plant companies divided the planning into two levels, general coordination, which can be understood as a company level, and multi-plant coordination, which aims to coordinate the different individual plants (Bhatnagar et al., 1993). It concludes that coordination just at the first level oversimplifies the relation of production with the demand and the situation at the plant level. When analysing this second level, the study highlights three issues that arise when attempting multi-plant coordination: the importance of properly evaluate and size the capacity constraints of each plant, the necessity to be able to adapt to nervousness on the demand without disrupting production planning in the rest of plants, the significance of properly dimensioning safety stocks. These issues have been later addressed by several studies corroborating the thesis (HEATH & JACKSON, 1994; Nascimento et al., 2018; Su et al., 2007, p.).

This report presents the work carried out to analyse the production of Inntre Kjeldstad. This is done by first building a material flow analysis model at the company level, formed by simplifications of the system of all the plants that compose the company. The system of the company is defined by interconnections between processes and plants, limitations of the production and interactions with external actors. This expands the scarce applications of MFA methodology at the plant and company levels. Also, contributes to the existing literature about the sawmill industry by providing a much more detailed description of five different plant systems with capabilities of processing structural solid wood, panels and certain categories of engineered wood (glulam). Then, the model is used for quantifying the oven-dry mass of wood flowing through the company with a specific focus on quantifying the use of transport of semi-finished and finished goods from plant to plant (in tonne-kilometre and the associated CO_2 emissions). The knowledge gathered through this analysis will contribute to the understanding of the use of wood by the forestry industries of the Trøndelag region. In this thesis, it is also used to build a second model that allows to simulate the implementation of transport-reducing strategies and analyse their potential impacts on every plant's production.

The description of the system and the models is described in the Methodology section. The quantifications of oven-dry mass and CO_2 emissions are reported under the Results sections, as well as the outcomings of the simulated strategies. The interpretation of the whole set of results can be found in the Discussion.

1.4. Research questions

In summary, this thesis aims to answer the following questions by analysing the material flow of Inntre Kjeldstad at the plant and company level:

- How and in which amount is wood being used by a multi-plant sawmill company in the Trøndelag region?
- How are the plants connected by the trade of semi-finished and finished products within the company?
- What impacts in each plant's production would have a reduction of the trade of goods between plants?

2. METHODOLOGY

The study of the company has been conducted through a Material Flow Analysis, being wood's use the material to examine. This section will describe the System Definition required for such analysis, how it has been quantified and the development of CO_2reducing strategies.

System definition explains the activities, functioning and organization of the company. This is necessary knowledge to afterwards be able to model and analyse the data because it defines the connections of flows and the limitations of the system. Its outcome is shown in the System Diagram Figure 1. Quantification explains how the overlay of the data over this system understanding has been deployed, and the limitations and weaknesses derived from the assumptions taken during the process. The CO_2reduction strategies are based on a mathematical model, described in the third section 2.3.

2.1. System definition

2.1.1. BOUNDARIES

The sawmill company under study is a merger of former Inntre AS and Kjeldstad Trelast. Its activities are based in the region of Trøndelag, where its 6 plants are located (Steinker, Verdal, Snåsa, Selbu, Levanger and Støren). Its main activity is the production of wooden building material, both structural and finishing. All the plants are able to produce products ready to be sold in the market out of roundwood, except for Snåsa and Levanger, whose production requires a supply of an intermediate product. However, all the plants work in synergy; there is an intensive use of inter-plant transport. The technological differences between plants allow some sites to produce product categories that are not feasible for others.

General information about the technicalities of the sawmill industry has been gathered from published literature. Information about the operation of each plant and the company's operation as a whole have been obtained through a series of interviews with the Operation Managers of the plants, email conversations and plant visits carried out between February and June 2021 (Jon Kjesbu et al., personal communication, 4 March 2021; Lars Ival Sundal & Håvard Kjesbu, personal communication, 10 March 2021). Specific details on the functioning of certain processes, workflows within the plants and product categories were acquired during the plant level study of Selbu carried out between September and December 2020 (Las Heras Hernández, 2020).

The following diagram is a simplification of the several stages of the production of the company and has been the baseline framework for the whole project on which quantification and modelling have been conducted.

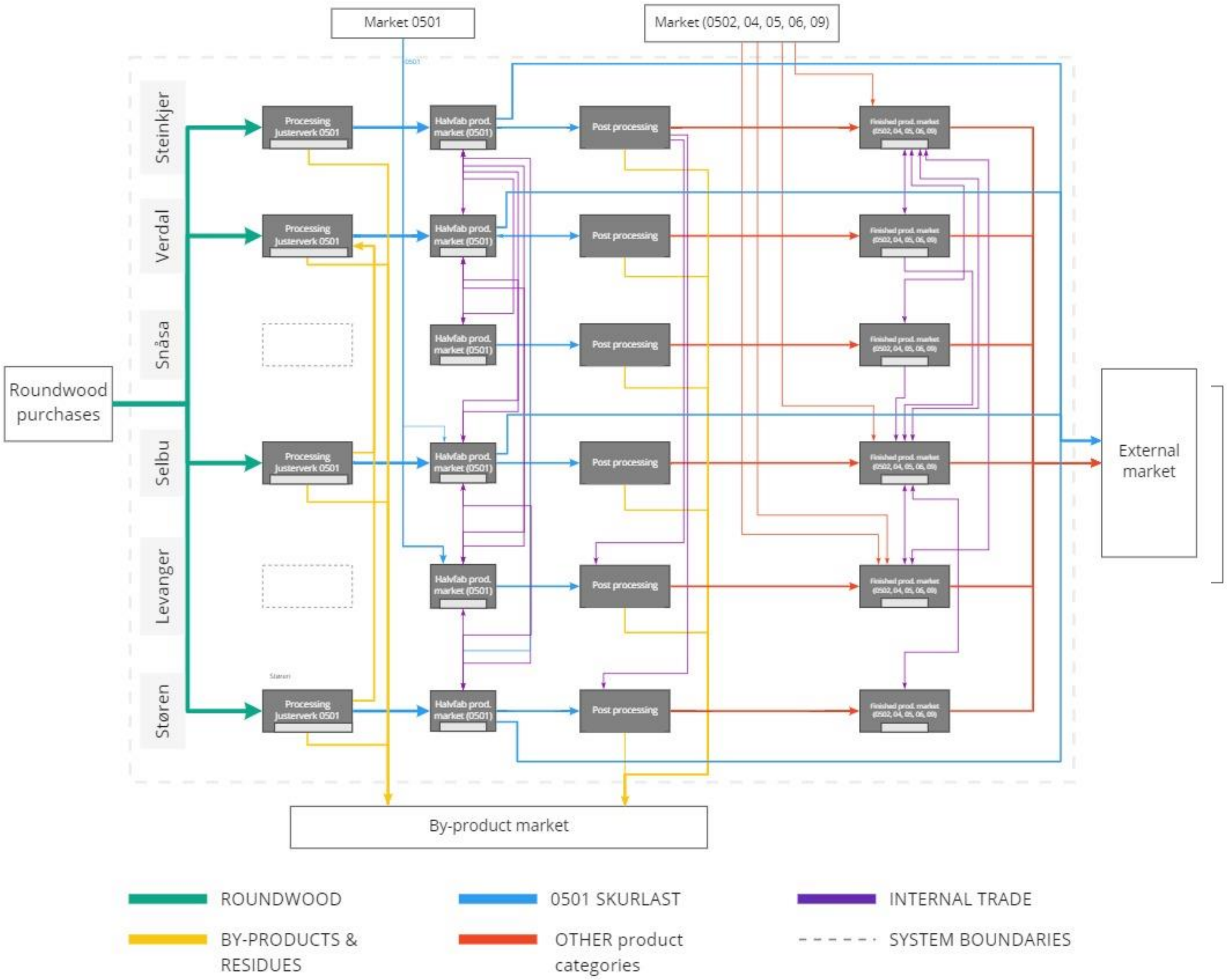

Figure 1 System diagram - Company level

The System Diagram has been structured combining the individual production layout of each plant and their interlinkages, as well as the links with external markets, following a similar arrangement as some other MFAs that accurate showcase transactions of material (Liu & Müller, 2013; Singer & Donoso, 2007). The light grey dashed line represents the System Boundaries: elements contained within its limits are the main focus of this study.

Inside the system

Processes

Each row embodies a Plant, where the wood flows through 4 different processes (grey boxes). These boxes are organized in 4 columns because they represent different stages during the production that are common to all the plants. Each of these stages aggregate several processes carried out at the plant level:

- ***Justerverk*[1] processing**. It aggregates Roundwood reception, storage of Roundwood, infeed, debarking, sawing, drying, adjusting and quality control. After this, products are

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[1] Norwegian terms commonly used within the company will appear *in italics.*

ready to be sold to the market, but can also move further into post-production to conform new Product categories. It does not exist for Snåsa and Levanger because these plants do not have these technologies in their sites.

- **Semi-finished products market**. It aggregates External and internal purchases and sales of *Justerverk's* outcome, its storage and its sorting for use in further post-processing.
- **Post-processing**. It aggregates every secondary process done to the products that upgrade them to a new Product category. These processes can be planing (*Høvel*), fingerjointing (*Fingerskjøt*), laminating (*Limtre laminering*), pre-cut, brushing (*Børsting*), painting (*Beis*) and impregnating (*Impregnering*).

  Not every plant has the same available technology, so the produced Product categories are different depending on the plant. The following section shows the process availability for each plant.
- **Finished products market**. It aggregates External and Internal Purchases and Sales of Post-processing outcomes, and its storage.

Stocks have been introduced in the market processes to capture the accumulation and storage of goods after production and trade. Similarly, stocks have been introduced in *Justerverk* processing to capture the accumulation of received Roundwood before it is fed into production.

Substances and Products

The operations are run on softwoods. The whole company works with wood from two types of tree, predominant in the Norwegian region where the activities are based (SSB, n.d.-c):

- Norwegian Spruce (Picea Abies)
- European Red pine (Pinus Sylvestris)

All processes can be performed on both wood types except for impregnation, which can only be applied to Pine wood. Due to this, some of the product categories are composed of a mix of pine and spruce products. However, spruce is the main used wood by the company, reaching over 85% of the production.

The combination of different production methods results in several product categories, that from now on in this report will be referred to as per the Norwegian term used within the company: *Salgsgrupper*. These *Salgsgrupper* have been aggregated at a level equivalent to the NOBB *Hovedgruppe*, codes used as Norwegian industry-standard (Norsk Byggtjeneste AS, n.d.).

Therefore, even though the substance used in all the stages of the production is primarily wood, its form is modified during *Justerverk* processing and post-processing. The colouring of the arrows in the diagram indicates the state of the wood on each of them, from the initial roundwood until the finished products and also included the by-products generated. The materials existing during the production are aggregated as follow:

- **Roundwood**. Received pine and spruce logs from the felling industry.
- **0501 *Skurlast***. It is the outcome of *Justerverk* process. It is the most basic product ready to be sold to the market and is the primary product from which all other products are produced.
- **0502 *K-virke***. Planks to be used as structural elements in construction.
- **0504 *Utvending Kledning***. Exterior cladding and finishing for building walls.
- **0505 *Innvending Panels***. Panels for finishing of interior walls.

- **0506 *Høvellast*.** Aggregation of a broad range of planed products, e.g. terrace and roof boards.
- **0509 *Konstruksjoner*.** Glulam products used for structural tasks in construction.
- **1512 *Parkett- og Tregulv*.** Boards used for covering indoor floors.
- **By-products.** This aggregates all different categories of by-products regardless of whether they are dry or raw (e.g. bark, cellulose chips, sawdust, wooden shavings, briquettes…). Even though in the production by-products are separated by their use (whether it is as fuel for the kilns or as external sales), here they will be considered as a single flow.

From now, the term **OTHER** will be used to refer to the product categories **0502, 04, 05, 06, 09** and **1512**, when it is necessary to talk about all post-processed products at once.

The flows and the trade

Two main directions are defining the material flows in the diagram: vertical and horizontal. These two dimensions represent two main usages given to the materials in the plants:

- **Horizontal**: internal use of the materials by a plant, i.e. the use within the production line of a plant to manufacture goods out of raw material.
- **Vertical**: trade of goods with external parties, or between the company's plants.

The arrows depicting trade with external parties are coloured according to the *Salgsgrupper* flowing through them.

The purple arrows depicting trade between plants are a simplification of the real trade flows to ease the understanding of the diagram. They are conformed by a mix of *Salgsgrupper*, variable from plant to plant, and therefore the colour does not showcase the *Salgsgrupper*. In addition, not all the connections are showcased in the diagram. To ease the visualization of the diagram and avoid an overcrowded unintelligible mess, only the main trade flows have a corresponding arrow.

The internal trade between plants can be separated by the *Salgsgrupper* traded, and it is visualized in the arrows flowing between the processes in the 2nd and 4th columns of the diagram.

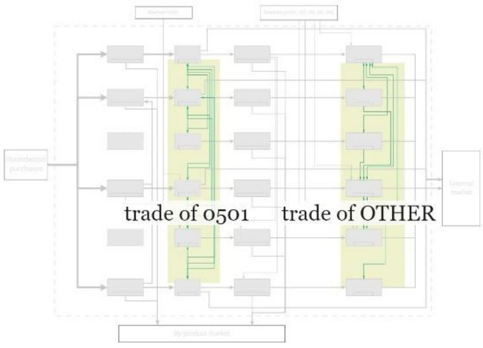


Figure 2 Explanation of trade

- **Trade of 0501.** It is the trade showcased in the 2nd column. These products are traded to be further processed in the receiving plant.
- **Trade of OTHER**. It is the trade showcased in the 4th column. These products are traded to be sold to a customer from the receiving plant. They will not receive any further processing. This is done this way to be able to supply the customers with complete batches of products shipped from a single plant, even though the products might be produced in different locations.

The Plants

Each of the plants has certain singularities on their production that define which *Salgsgrupper* can be produced, and that sets certain limitations to their production that shall be considered when modelling the production capacities of the whole company. The following diagrams describe the production in each of them.

› **Steinkjer** –system diagram

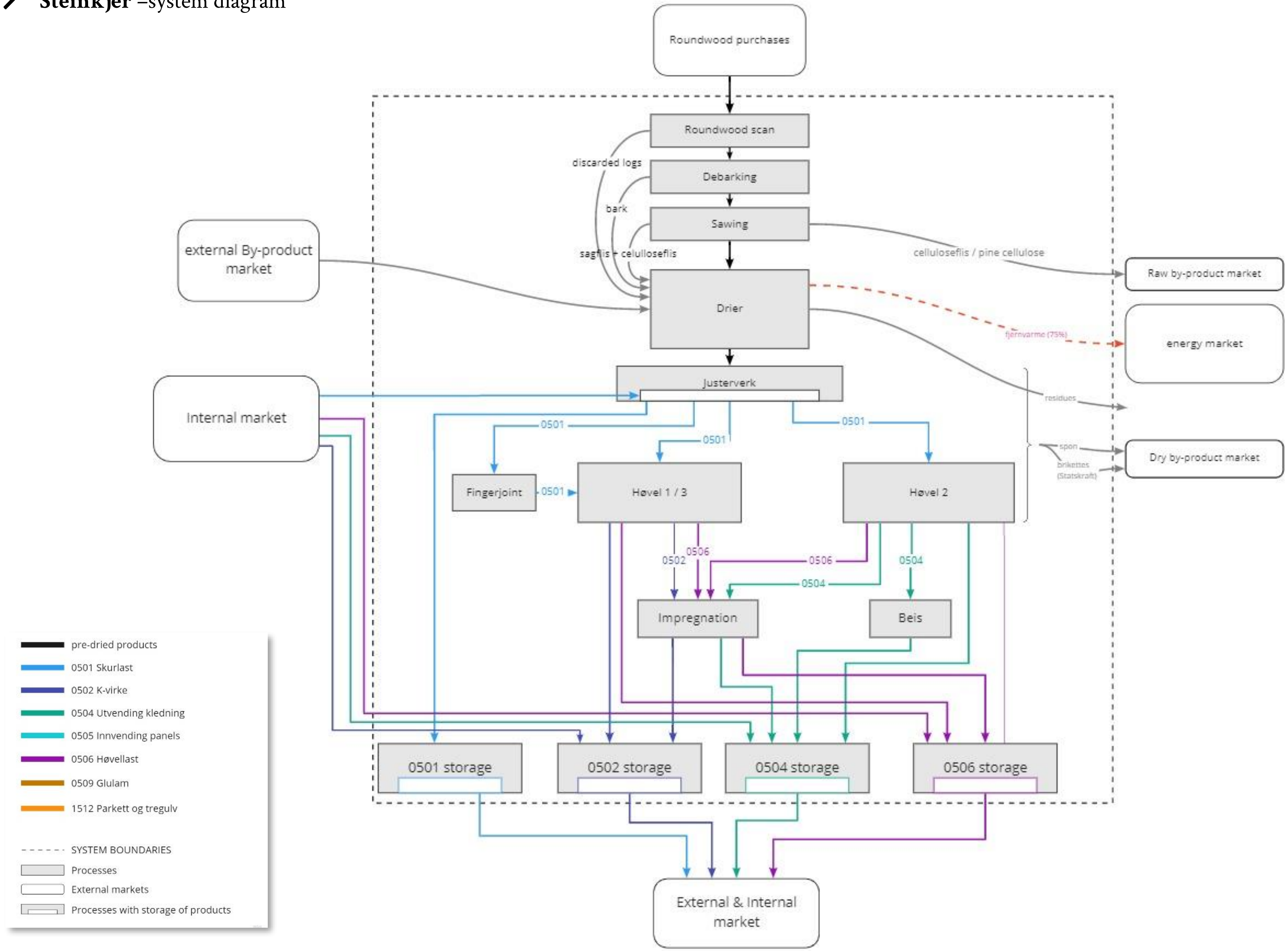


Figure 3 System diagram - Steinkjer

Verdal – system diagram

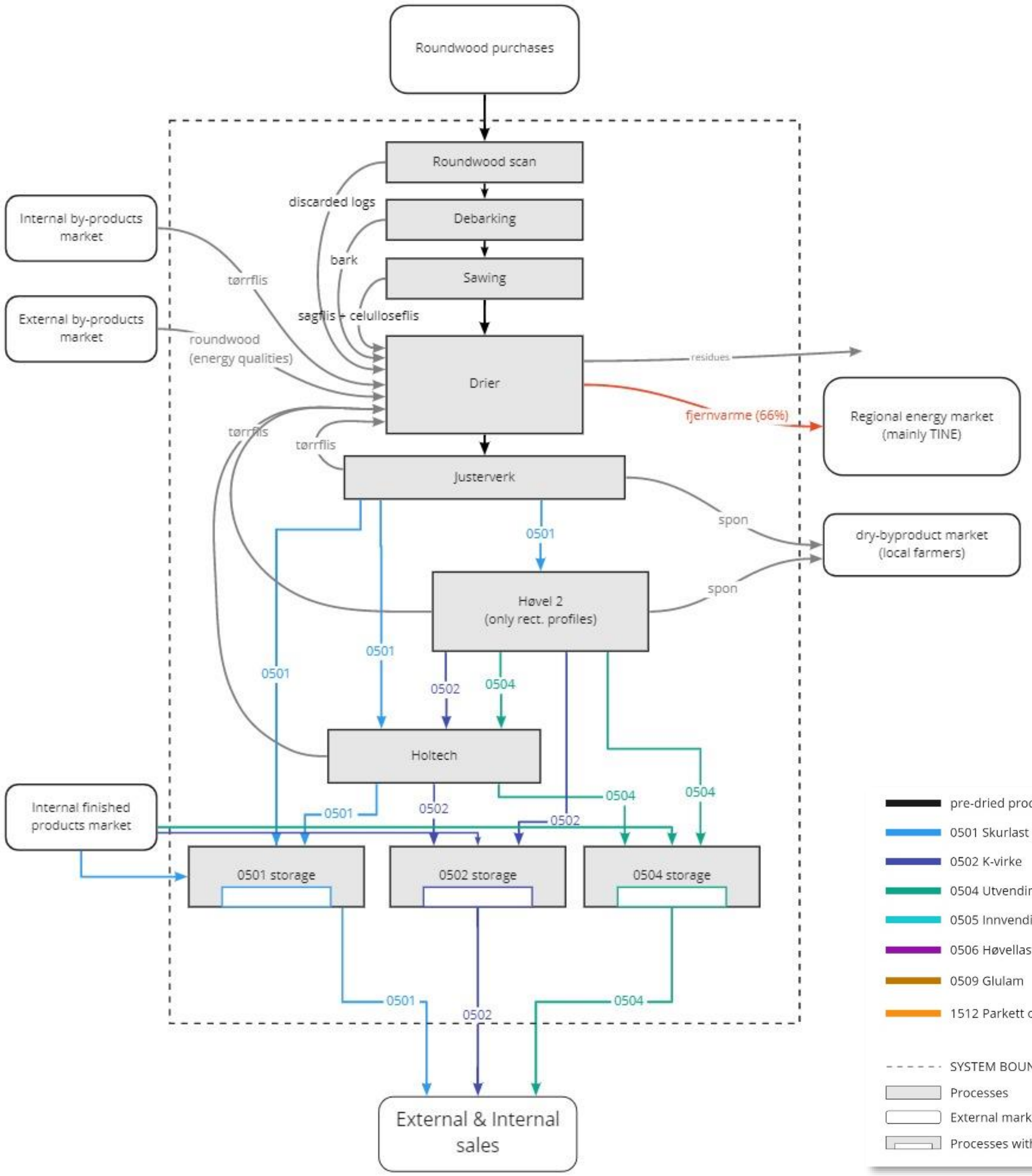


Figure 5 System diagram - Verdal

Levanger – system diagram

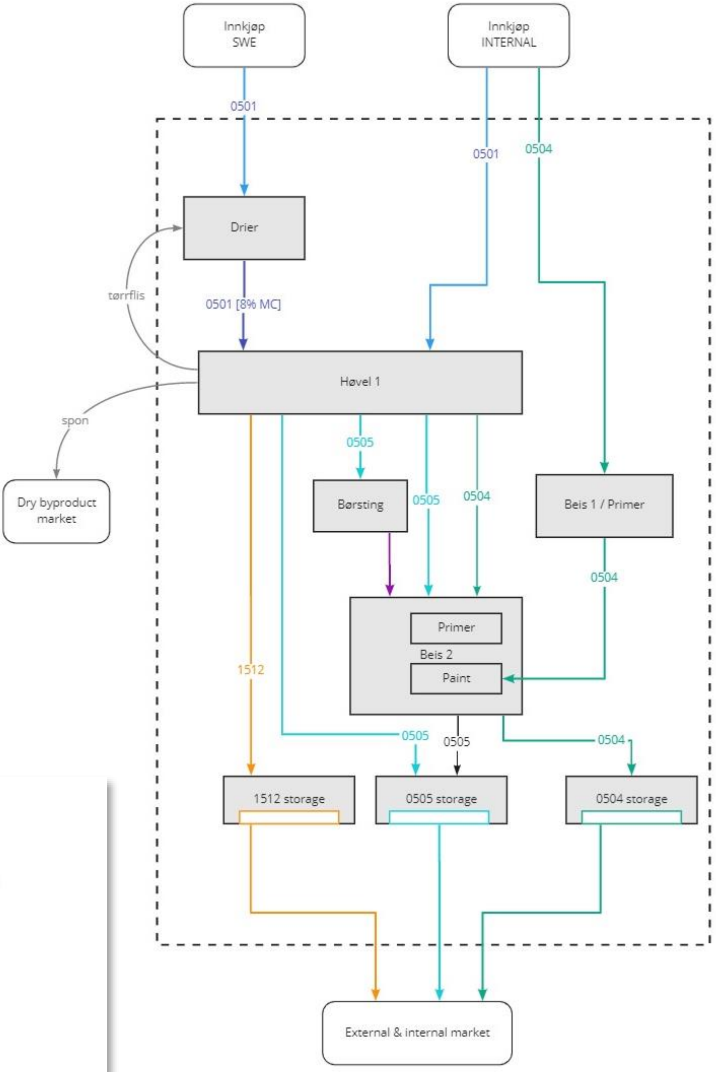


Figure 4 System diagram - Levanger

Selbu – system diagram

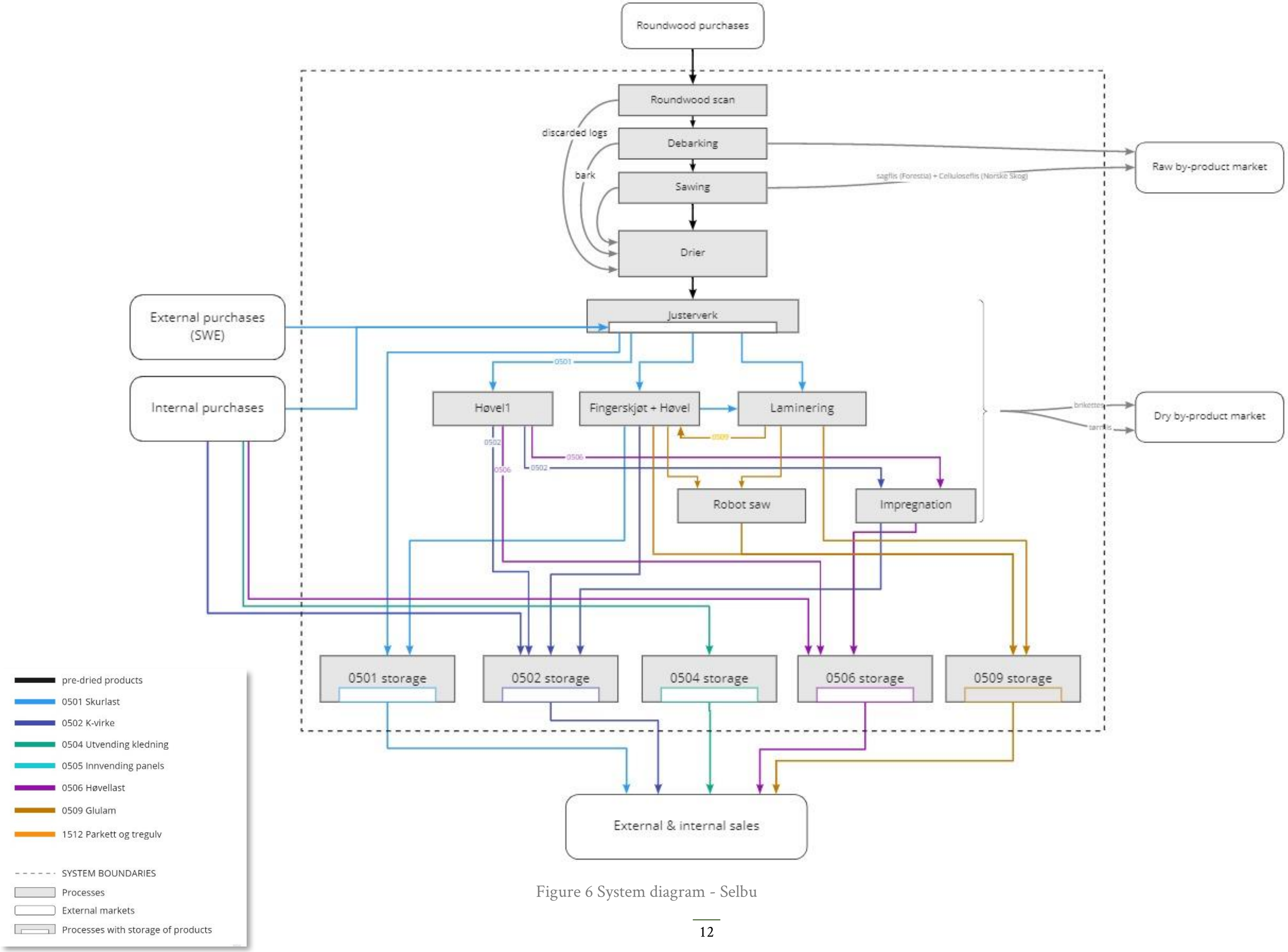


Figure 6 System diagram - Selbu

› **Støren** – system diagram

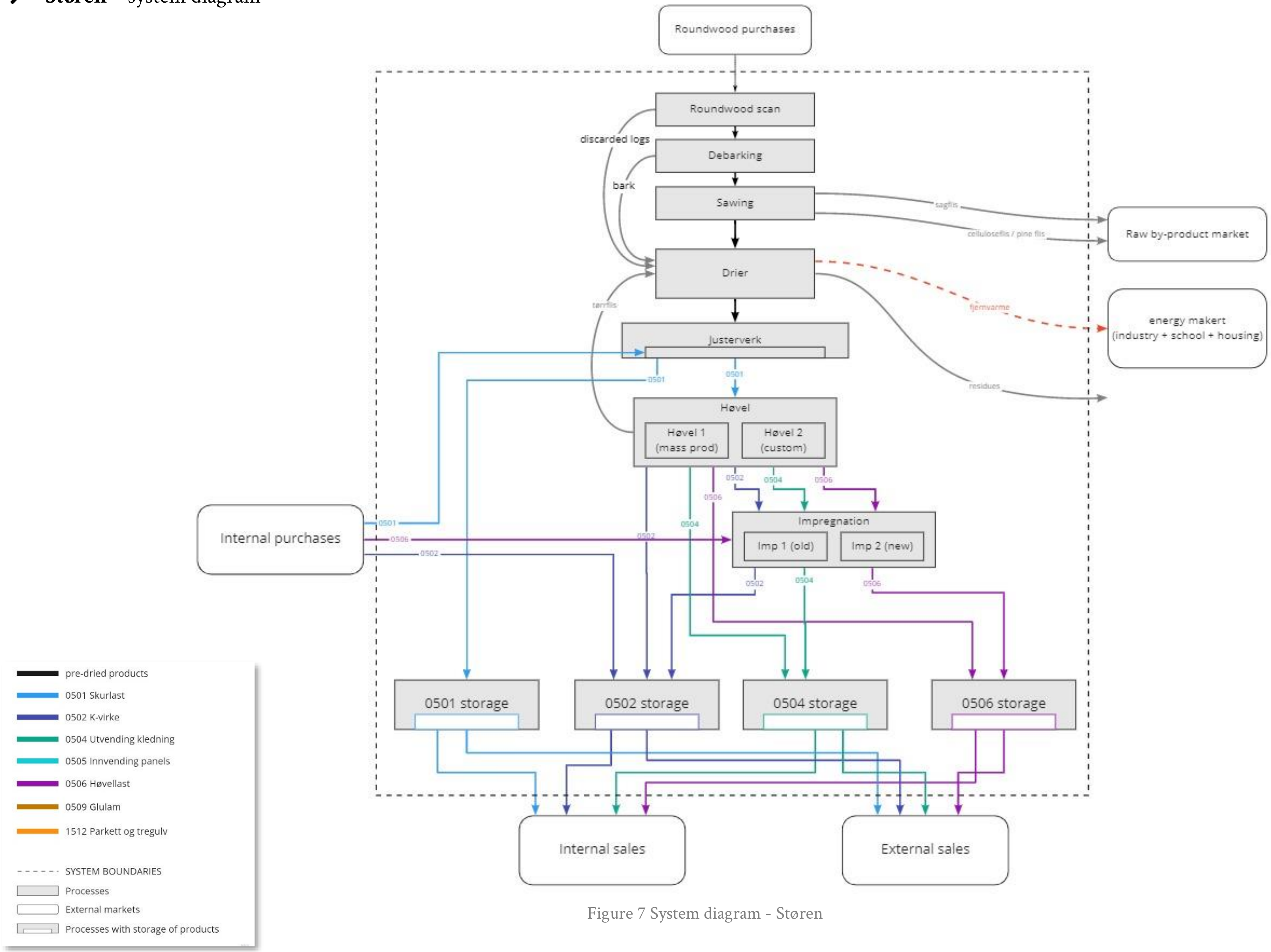


Figure 7 System diagram - Støren

❯ Steinkjer

It is the biggest plant of the company in terms of site area, overall production, sales and available technologies. It is the main node of the company in the North, and thanks to its closeness to Trondheim's fjord it is the company international sea connection.

The previous diagram Figure 3 presents the production line in the plant. Steinkjer has the technology to produce 4 of the *Salgsgrupper*: 0501, 02, 04 and 06. The different planers (*Høvel* 1, 2 & 3) allow the plant to create both rectangular and engraved profiles. This, along with the impregnation line enables the production of every subcategory of *Salgsgrupper* 0504 and 0506.

The planing capacity of the plant is often close to its limits, creating a bottleneck at this stage. However, a new automatized planing line is under construction, so higher planing capabilities are expected soon.

When the capacity of the impregnation line is reached, the production of 0504 that requires from this process is diverted towards Levanger.

❯ Verdal

Production in Verdal is focused on *Salgsgrupper* 0501 and 0502. The main characteristic of this plant is the strong focus on energy generation from production by-products. So much so that they have a specially designed kiln, whose energy is used in a bigger share for sales to nearby companies than for drying their products.

The previous diagram Figure 5presents the production line in the plant. Verdal has the technology to produce 4 of the *Salgsgrupper*: 0501, 02, 04 and 06. Although the lack of specific planers (*Høvel* 1 and 3) and an impregnation line, limits the production of the latter 2 *Salgsgrupper* to only rectangular profiles and non-impregnated products.

The processes that perform a transformation on the goods are assumed to not have any stock since the goods are flowing through them into the market processes.

The capacity of their driers is usually close to its limits, being the main bottleneck of their production of 0501 and therefore, also limiting the other *Salgsgrupper*.

The storage capacity of the plant is also a limiting factor, being usually close to full.

❯ Snåsa

This is by far the smallest plant of the company, dedicated especially to cover the production peaks that may occur in Steinkjer. It does not process its own 0501, and it does not sell products to external markets.

❯ Selbu

It is the company's biggest plant in the Southern area of the company, with similar production and sales numbers to Steinkjer. It is the only plant of the company capable of producing Glulam products, so its production is oriented towards this *Salgsgrupper*.

The previous diagram Figure 6presents the production line in the plant. Selbu has the technology to produce 5 of the *Salgsgrupper*: 0501, 02, 04, 06 and 0509. Although the lack of specific planers (*Høvel* 1 and 3), limits the production of the latter 2 *Salgsgrupper* to only rectangular profiles and non-impregnated products. The existence of a Glulam production line along with a Robot saw allows the plant to create customized construction packages and creates a more complex flow of materials in the production than in other lines.

The driers in Selbu are currently working at full production during the whole year. This creates a rigid limit for 0501 production in the plant.

› Levanger

It is one of the tiniest plants of the company. All the 0501 used for its production comes from either external or internal trade because it does not have a sawing line, required for this *Salgsgrupper* production. It is specialized in surface coatings, such as premier and paint, for external cladding and interior panels. It is the only plant of the company capable of priming and painting Interior panels.

The previous diagram Figure 4 presents the production line in the plant. Levanger has the technology to produce 3 of the *Salgsgrupper*: 0504, 05 and 1512. The production of this plant is the most different from the rest of the company due to its focus on the production of finishing boards, instead of structural products. Even though it does not produce 0501, it counts with a drier that is used to ensure the quality of certain pinewood products purchased from Sweden.

Storage capacity is the main limitation for this plant, which is also the smallest one in terms of available surface area.

The capacity of its painting line is shared by the *Salgsgrupper* 0504 and 0505. This implies that an increase in the production of one would entail the same reduction on the other one.

› Støren

It is the southernmost plant of the company. The distribution of its production is rather similar to Steinkjer but with a smaller capacity. Its most specific line is dedicated to impregnation, mainly of 0506 products which are used in exteriors. It is the plant that uses the most pine of the 6, purchasing it from the southern areas of Trøndelag.

The previous diagram Figure 7 presents the production line in the plant. Støren has the technology to produce 4 of the *Salgsgrupper*: 0501, 02, 04 and 06. The combination of planers allows the plant to produce all the products within 04 and 06 offered in the company's catalogue. Its impregnation lines are also used to contribute alleviate peaks of production in Steinkjer.

Loading times of the drier and drying cycles are the main limitation for this plant, which is also the smallest one in terms of available surface area.

The capacity of its planer line is also a restriction but is currently being upgraded to speed up its processing.

Outside the system

The elements outside the grey dashed line on the Company Diagram (Figure 1) are parties that interact with the company either providing materials or purchasing them.

Selling markets

The felling industry sells the roundwood to the company used in the production. It is mainly comprised of companies based in the region. Each plant buys from different suppliers according to their location, except for most of the pinewood supplies that come from Swedish forestry due to the higher quality of the wood (Jon Kjesbu et al., personal communication, 4 March 2021).

Some intermediate and finished products are bought from other sawmill industries. This is the case for Levanger purchases of pinewood 0501, used on the production of 0505, and purchases of certain sizes of 0509 that are not producible by Selbu.

Purchasing markets

The outcomes of the company production can be in the shape of products or by-products. Both have their own purchasing markets, composed of several industries and located in a broad range of regions and countries. In this study, they are aggregated by Product and By-product purchasers, but it is relevant to highlight the different parties conforming to them.

The main products are sold to wholesalers of construction materials, manufacturers of secondary products and directly to end customers. These are located both along with Norway and internationally.

The by-products are sold to manufacturers of secondary products (e.g. papermill industry Norske Skog and Mm Karton Follacell), bioenergy producers, farmers (mainly wood shavings used for the conditioning of barns) and end customers.

A more in-detail description of Processes, Products and Substances can be found on the report developed at the plant level for Selbu during the Fall 2020 (Las Heras Hernández, 2020).

2.2. Quantification

The System Definition presented in the sections above has been used as a base wireframe to quantify the material flows in the company. The quantification has been carried out for two different layers: Mass and CO_2 emissions due to internal transport.

The mass flows have been quantified for all the flows in the system. The emissions have been only quantified for the flows of internal transport, other sources of emissions such as energy use for production or external transport are not included in the analysis. This is due to the different scopes of study for each substance: at the wood level, this report is interested in analysing the whole system and its interconnections, while at the emissions level it focuses on the use of transport between the plants.

2.2.1. TIMEFRAME & DATA SOURCES

The study has been carried out with data from the year 2020. Even though for many industries this has been a year with decreased sales due to the Covid-19 pandemic, the company has reported a stable overall sales balance.

The data used has been provided by Inntre Kjeldstad, and it is a combination of reports from all the plants. All the numbers are disaggregated by product category and Plant on a monthly basis. These reports cover the following activities of the company:

- Purchases and Sales of products to internal and external markets.
- Purchases of Roundwood and other secondary products utilized during production.
- Sales of by-products to external purchasers
- Usage of storage.
- Usage of products by the plants during production

The data provided reports amounts of products in cubic metres and a mix of units for the sales of by-products that depend on their form when being sold.

2.2.2. MASS

The Mass dimensions of the system is a quantification of the oven-dry weight of wood in each of the flows (Walker, 2006).

The parameters and equations will be explained for a single plant (a row in the company diagram Figure 1). The rest of the system is calculated in the same way, iterating the structure for each of the plants and applying the corresponding parameters.

Parameters

There are two main types of parameters in the system. Measured Data provided by the company and ratios and specific gravities gathered from literature or the company's documentation.

Measured Data

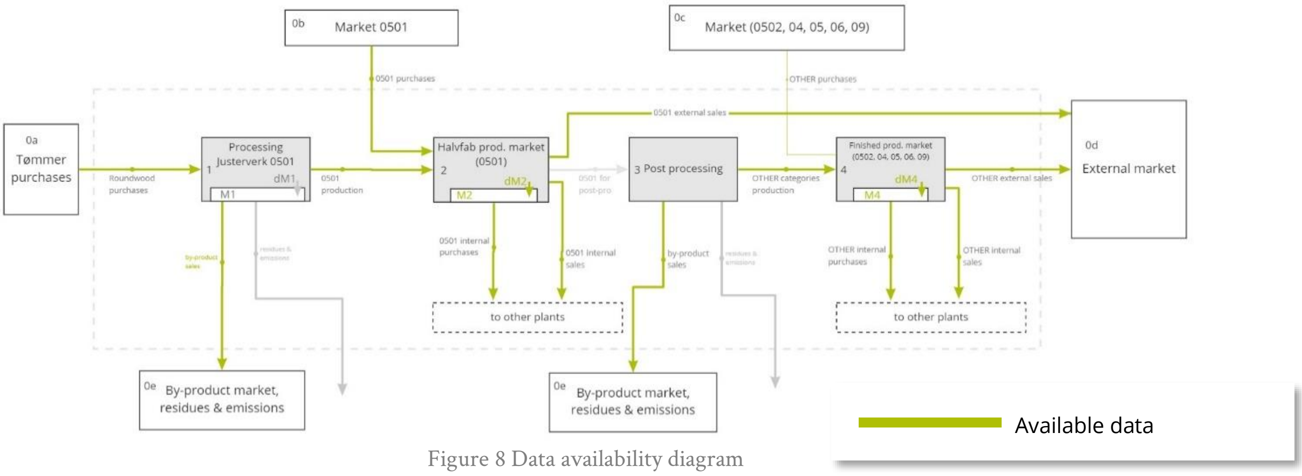


Figure 8 Data availability diagram

The figure above shows the location of the reported data in the system. Green coloured arrows indicate data covered by the reports.

Here there are comprised the reported purchases, sales, stocks, stock variations of the system and production volumes. All these are direct measures of the system done by each plant and constitute a high-quality data source. This data is the core of the System Quantification, and most of the equations have been built over it.

The parameters referring to **Internal** and **External Purchases** are disaggregated by the different *Salgsgrupper* and by the company/plant where the purchase has been made from. **Internal** and **External Sales** are equally disaggregated by *Salgsgrupper* and destination external market/plant.

Stocks, **Stock changes** and **Production volumes** are similarly disaggregated by *Salgsgrupper*. All these numbers reporting products in the system are given in volume (m^3).

The parameters referring to **Purchases of Roundwood** are given in m^3 of roundwood without bark. Although, the material arriving at the plants is not yet debarked, and one of the by-products generated during production is the bark itself. This parameter is estimated and not directly measured; therefore, its uncertainty is higher than the rest.

The parameters referring to **Sales of By-products** are given in a range of units, depending on the shape the by-products are sold on.

Ratios, densities, specific gravities…

The following list of parameters has been used either to convert the Measured Data into a common unit or to make up for the lack of data in some of the flows of the system.

The following list breaks down the two categories, indicating each parameter value, source, related assumptions and reliability of the data.

The uncertainty of the following assumptions and the resulting parameters is represented by a colour scale ranging from red (rather uncertain) to green (highly reliable).

RATIOS / DENSITIES & SPECIFIC GRAVITY / OTHER…

SG_green_wood	0,36t/m3	specific gravity of GW spruce (oven dry weight / green volume)	(Miles & Smith, 2009)
SG_dry_wood	0,39t/m3	specific gravity of dry wood spruce (oven dry weight / 12%MC volume)	

Reported volumes of wood entering or leaving the system (aforementioned Purchase and Sales tables) are converted to dry matter mass. Since the dry matter content of $1m^3$ of wood is different depending on whether the wood is dry or not (the drying process entail a certain degree of shrinkage (Schulgasser & Witztum, 2015), two different parameters are being used.

The Quantification has been done by converting the different units of the data into the oven-dry mass of spruce wood. However, some plants process pine products as well, and 10% of the end sales are pinewood products. The basic density of *Picea abies* and *pinus silvestrys* are highly variable and dependant on many factors such as growing location, spacing, even height of the tree [Johansson, influence…][Sopushynskyy][Szaban]. The reported values range within the same brackets and therefore, it has been decided to normalize all the volumes with the same parameters (360 - 420 kg/m3) [references. Look in bg research doc].

bark_content	10%	the ratio of bark per m3 of clean log	(Krogell et al., 2012; Nosek et al., 2016; Picos et al., 2010)

Since roundwood amounts are given in estimated volume without bark, this value has been used as a conversion for "*clean log*" mass into "*log with bark*" mass.

bark_d	0,205t/m3	bulk density of spruce bark	(Routa et al., 2020)
raw_sawdust_d	0,145t/m3	bulk density of raw sawdust	(Vidrine & Woodson, 1982)
dry_sawdust_d	0,145t/m3	bulk density of raw sawdust	
spon_d	0,156t/m3	bulk density of shavings	
cf_d	0,180t/m3	bulk density of cellulose chips	(FAO Forestry Department, 2004; McKendry, 2002)
briquett_d	0,600t/m3	bulk density of briquettes	

Reported volumes of by-products also require conversion into dry matter. However, this step is more complex because they are composed of loose particles. The differences in compression lead to high variability on their bulk densities. Besides, the particle composition of the goods makes them more likely to rapidly modify their MC while being stored due to the easier water absorption/evaporation (Lars Ival Sundal & Håvard Kjesbu, personal communication, 10 March 2021). Due to this, raw and dry sawdust are assumed to have similar bulk densities, considering their transportation through air pipes to the storage point. These factors make these parameters assumption highly uncertain.

Table 1 Description of parameters: Ratios, densities & specific gravities

saw_yield	55%	average production ratio of Sawing
juesterv_yield	95%	average production ratio of *Justerverk*

APPENDIX 3

The previous ratios are provided by the company and are averages drawn from measurements and experience. However, is important to highlight that these ratios are subjected to fluctuations driven by variations in the amounts of finished products manufactured. Some processes, such as sawing, may perform different operations when producing different goods (Lars Ival Sundal & Håvard Kjesbu, personal communication, 10 March 2021).

Table 1 Description of parameters: Ratios, densities & specific gravities

Description of the flows

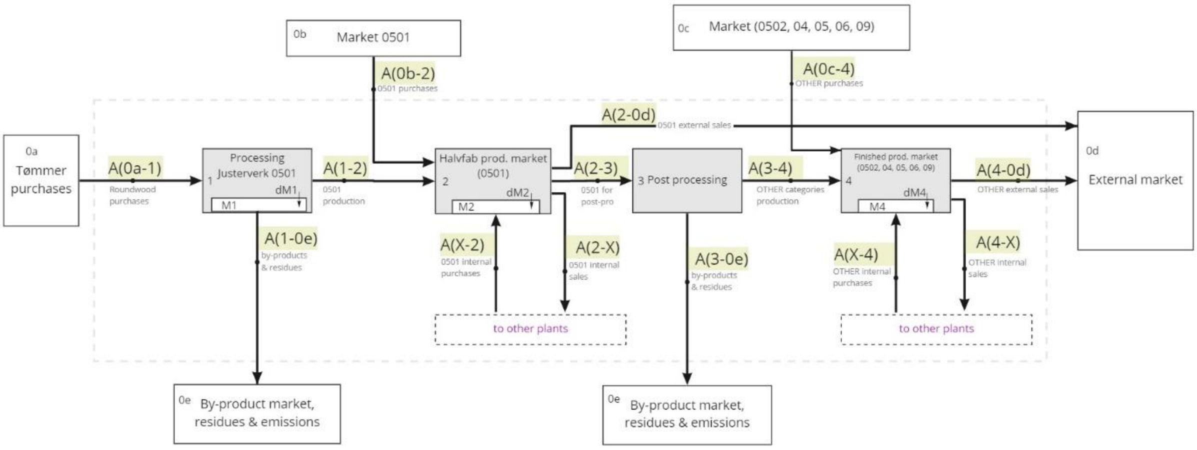


Figure 9 Description of the flows: Plant simplification

The calculations of the flows can be divided by whether they are direct conversions of Measured Data or derived from other flows and ratios.

Direct conversions

The equations describing these flows share a common structure where the `Measured Data` (parameter in dark green) is converted into oven-dry weigh using other parameters (parameters in light green).

The uncertainty of the parameter `SG_dry_wood` is highly uncertain, which makes the quantification of the mass of each of these flows rather uncertain. However, since the study has a stronger focus on comparing the different ratios along with the production, and not that much of analysing the real mass of the wood in the system, the quantification of these flows has been assessed as low uncertainty. Variations on that parameter would equally modify all the values, leaving the system unchanged. There is an exception in Roundwood purchases, that both use a different conversion factor, and its reported data is also uncertain.

Roundwood purchases (`A0a-1`) high uncertainty

Purchases of roundwood by a company from every supplier. Converted into dry mass and factorized by bark content.

```
A0a-1 = roundwood purchases x SG_green_wood x (1 + bark_content)
```

0501 production (`A1-2`)

Finished 0501 after *Justerverk* process that conforms the plant's own supply of *Skurlast.*

```
A1-2 = 0501 production x SG_dry_wood
```

0501 external purchases (A0b-2)

Aggregates the purchases of 0501 from different suppliers that will be used for post-production.

```
A0b-2 = 0501 external purchases x SG_dry_wood
```

0501 internal purchases (AX-2)

The X stands for the plant where the purchases are made from. Even though the diagram shows a single flow, in the model this flow is disaggregated for each plant (it is hence 6 incoming flows). The equation shall be adapted with the corresponding purchases.

```
AX-2 = 0501 internal purchases from X plant x SG_dry_wood
```

*the X stands for the origin plant

0501 external sales(A2-0d)

Aggregates the sales of 0501 to different buying markets outside of the company.

```
A2-0d = 0501 external sales x SG_dry_wood
```

0501 internal sales (A2-X)

The X stands for the plant to which the product is being sold. Even though the diagram shows a single flow, in the model this flow is disaggregated for each plant (it is hence 6 outgoing flows). The equation shall be adapted with the corresponding sales.

```
A2-X = 0501 internal sales to X plant x SG_dry_wood
```

*the X stands for the destination plant

0501 Stock and Stock changes (M2 and dM2)

Storage of 0501 and its variation at the end of the year respect from the beginning.

```
M2 = 0501 stock x SG_dry_wood
```

```
dM2 = 0501 stock variation x SG_dry_wood
```

OTHER production (A3-4)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each *Salgsgrupper* resulting from post-production (it is hence 6 outcoming flows, varying from plant to plant). The equation shall be adapted with the corresponding production.

```
A3-4(050X) = 050X production x SG_dry_wood
```

*the number between brackets stands for the *Salgsgrupper*

OTHER external purchases (A0c-4)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each purchased *Salgsgrupper* (it is hence 6 incoming flows, varying from plant to plant). The markets suppliers are aggregated as a single one.

```
A0c-4(050X) = 050X external purchases x SG_dry_wood
```

*the number between brackets stands for the *Salgsgrupper*

OTHER internal purchases (AX-4)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each purchased *Salgsgrupper*. Each of the *Salgsgrupper* purchases is also disaggregated by the plant from which the product is being bought, which is represented by the X (it is hence 36 incoming flows, varying from plant to plant).

`AX-4(050X) = 050X internal purchases from X plant x SG_dry_wood`

*the number between brackets stands for the *Salgsgrupper*

*the X stands for the origin plant

OTHER external sales (A4-0d)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each sold *Salgsgrupper* (it is hence 6 outcoming flows, varying from plant to plant). The markets suppliers are aggregated as a single one.

`A0c-4(050X) = 050X external purchases x SG_dry_wood`

*the number between brackets stands for the *Salgsgrupper*

OTHER internal sales (A4-X)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each sold *Salgsgrupper*. Each of the *Salgsgrupper* sales is also disaggregated by the plant to which the product is being sold, which is represented by the X (it is hence 36 outcoming flows, varying from plant to plant).

`A4-X(050X) = 050X internal sales to X plant x SG_dry_wood`

*the number between brackets stands for the *Salgsgrupper*

*the X stands for the destination plant

OTHER Stock and Stock changes (M4 and dM4)

Storage of OTHER and their variation at the end of the year respect from the beginning. Both stocks and their variations are disaggregated by *Salgsgrupper* in the model.

`M4(050X) = 050X stock x SG_dry_wood`

`dM4(050X) = 050X stock variation x SG_dry_wood`

*the number between brackets stands for the *Salgsgrupper*

> It is important to highlight that when considering the whole company system, the flows of Internal Sales and Purchases are strongly linked. For instance, the Internal Sales from Steinkjer to Verdal of certain *Salgsgrupper* will be equal to the Internal Purchases of Verdal from Steinkjer:
>
> A2-B = BA-2 ; trade of 0501 from Steinkjer to Verdal
>
> A4-B(0504) = BA-4(0504) ; trade of 0504 from Steinkjer to Verdal
>
> *If Steinkjer = A ; Verdal = B

Derived from other flows

The equations describing these flows rely on the mass balance principle or some of the previously presented parameters (parameters in light green) used as transfer coefficients from other flows (names in dark green) is converted into oven-dry weigh using other parameters.

The uncertainty of these flows is indicated case-by-case.

By-products & residues generation from *Justerverk* processing `(A1-0e)` `high uncertainty`

From debarking roundwood to the final dimensional adjustments done during *Justerverk* process there are raw and dry by-products being generated. They are either sold to the market or used as fuel for the kilns. These uses vary from plant to plant, so this flow aggregates all of them regardless of their use. It is calculated based on the 0501 production `A(1-2)`, the Sawing and *Justerverk* production yields and roundwood bark content. Since it is based on several uncertain parameters, it is a highly uncertain flow.

$$A1\text{-}0e = \left(\frac{-1}{saw\_yield \times jv\_yield \times (bark\_content - 1)} - 1\right) \times A1\text{-}2$$

Roundwood Stock changes `(dM2)` `high uncertainty`

There is only data available for the purchases of Roundwood, but not for the use of it. Therefore, the stored amount and its variations are unknown and calculated through the mass balance of the *Justerverk* process. Since it is based on a flow with high uncertainty, it is also a not-so-reliable flow.

```
dM2 = A0a-1 - (A1-2 + A1-0e)
```

0501 for post-production `(A2-3)` `low uncertainty`

Mass of 0501 composed of products internally produced, bought from other plants and externally purchased. It is the material from which the rest of the *Salgsgrupper* is produced. Due to the lack of Measured Data, it is calculated through the mass balance of the 0501 market process. Since it is based on all Data Measured flows, it has low uncertainty.

```
A2-3 = (A0b-2 + A1-2 + AX-2) - (A2-0d + A2-X + dM2)
```

By-products & residues generation from Post-processing `(A3-0e)` `low uncertainty`

Operations during post-production remove mass from the products, hence generating dry by-products. They are either sold to the market or used as fuel for the kilns. These uses vary from plant to plant, so this flow aggregates all of them regardless of their use. It is calculated through the mass balance of Post-processing. Since it is based on two Data Measured flows, it has low uncertainty.

```
A3-0e = A2-3 - A3-4
```

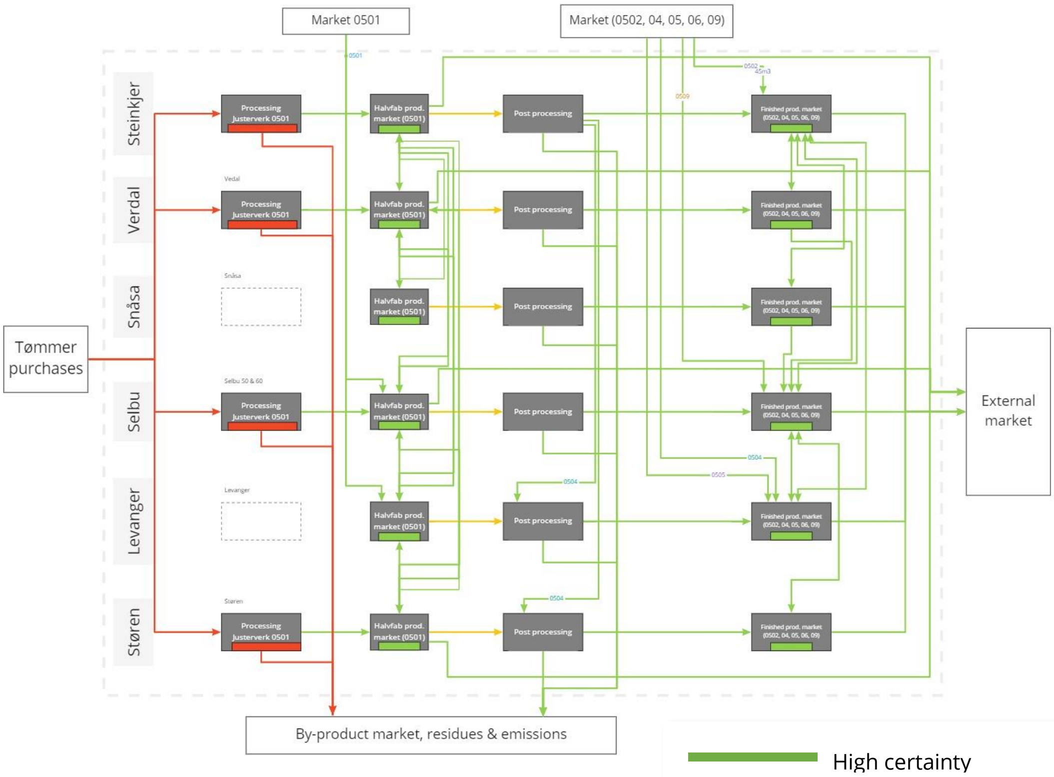
Data reconciliation & reliability of the model

Considering that the model is mostly based on highly reliable data captured by the company and that the whole system is mass balance consistent, data reconciliation is not considered key in the modelling process, and it has not been carried out.

It has been checked with the company whether the System Definition is in line with reality to avoid Systematic errors, and it has been approved.

Random measuring errors could appear in the Data Measurements done by the company, but their reporting method ensures that they are properly balanced out in the final accounting. The consistency of the Mass Balance of the system can therefore be trusted.

However, the certainty of some flows has been assessed to be low, which indicates that those values should be addressed under special consideration when analysing the results. The overall reliability of the flows is summarized in the following diagram. The level of certainty follows the same colour scale as in the section above.



🟩 High certainty
🟥 Low certainty
🟨 Medium certainty

Figure 10 Reliability of the model

2.2.3. CO_2 EMISSIONS

The quantification of CO_2 emissions in the system has been carried out only for the flows of Internal purchases, which are the ones following the structure `AX-2, AX-4(050X)`.

All the calculations are defined by the equation:

`CO₂ emissions of AX-4(050X) = AX-2 * distance from X-A * emissions intensity`

*the number between brackets stands for the *Salgsgrupper*

*the X stands for the origin plant, A stands for the destination plant

The distances from X-A are road distances (Google Maps, n.d.).

The emissions intensity used is the value for Specific CO_2 emissions per tonne-km for road transport in Europe in 2014: 139,8 g CO_2/tkm (EEA, n.d.-b).

Figure 11 Geographical distribution of the plants (SSB, n.d.-d)

DISTANCES BETWEEN PLANTS

FROM	TO		
Steinkjer	Verdal	32	km
Steinkjer	Snåsa	59,6	km
Steinkjer	Selbu	122	km
Steinkjer	Levanger	47,2	km
Steinkjer	Støren	170	km
Verdal	Snåsa	90,5	km
Verdal	Selbu	92,2	km
Verdal	Levanger	17,5	km
Verdal	Støren	140	km
Snåsa	Selbu	180	km
Snåsa	Levanger	105	km
Snåsa	Støren	228	km
Selbu	Levanger	75	km
Selbu	Støren	113	km
Levanger	Støren	123	km

Table 2 Description of distances between plants

This value has quite likely been reduced since then, which shall be considered when comparing with other emitting sources in the given timeframe, but it is not relevant for this study.

2.3. Emissions Reduction Strategies & Modelling

The analysis of the findings of the company's production and emissions generation commented in the Results has been used to suggest 4 different interventions that could potentially lead to a reduction of emissions through less intensive use of transportation between plants, e.g. modifications on the distribution of the production and internal trade. These interventions are modelled as Strategies, which are sets of modifications of some parameters that reconfigure the production and trade patterns.

Any modification on the production patterns risks leading to unfeasible solutions due to capacity or technology limitations. This has been assessed by analysing the impacts on each plant's production.

The **total emissions** are dependent on three factors.

`Total emissions = Transported Mass x Travelled Distance x Emission intensity`

The **emissions intensity factor** is dependent on the technology and the transport means, which is not within the scope of this study and therefore, is considered as a constant parameter. The strategies focus on a reduction of either the **mass**, the **distance** or the **combination** of both to reduce the total emissions.

The first set of strategies work as a Sensitivity Analysis, testing the modification of a single variable at a time. Significant modifications of just one variable led to strong asymmetries between plants, which highlights the backlashes of those modifications. The 4th strategy uses the knowledge acquired from the Sensitivity analysis to put together a better-balanced Strategy that allows an emission reduction with milder drawbacks for the production.

The description of each strategy, their reduction potential and their implications for the production are described in section 3.2.

To create different emissions scenarios and to assess the impacts of these modifications on the company production it is required to update the model defined for the quantification.

This new model uses the data from the quantification as a baseline and simulates alterations on the Internal Purchases and the variations caused on every plant's production. In this way, it models how emissions could have looked in 2020 if the simulated strategies were implemented while being able to supply the same external demand of products.

2.3.1. MODEL ADAPTATIONS

The model is set over the same System Definition previously described, with some exceptions.

External Sales remain the same to guarantee 2020 levels of production. The structure of Processes and the flows creating the connections between them also remain untouched. However, some flows are redefined.

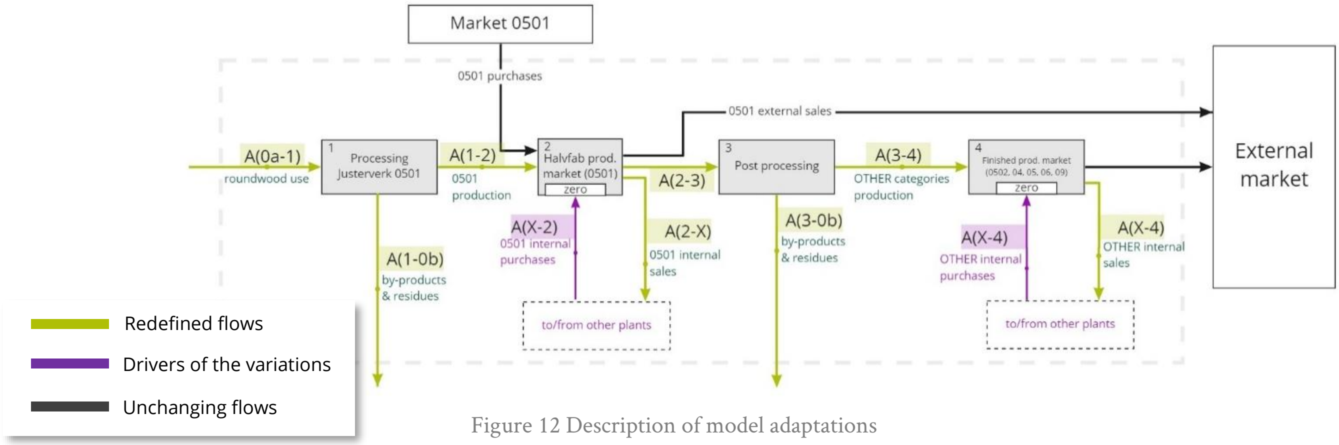


Figure 12 Description of model adaptations

Stock changes are set to zero, as the most desirable option after a whole production year. The stocks might vary during the year, but there will not be overall net changes.

Internal purchases of 0501 and OTHER (`AX-2 & AX-4`)

They drive the fluctuations in production. Two parameters are introduced to modify the baseline values according to the description of the strategies.

`AX-4(050X) = baseline purchases x purchases_shares x market_participation`

Internal sales of 0501 and OTHER (`A2-X & A4-X`)

As previously mentioned, the sales flows are equivalent to their corresponding purchases flows. Sales from plant A to plant B of a certain *Salgsgrupper* are equal to purchases of plant B from plant A of the same *Salgsgrupper*.

`AB-4(0502) = BA-4(0504)`

Byproducts and residues generation in processes 1 & 3 (`A1-0b & A3-0b`)

Both are calculated according to generations ratios derived from the Quantification for each plant.

`A3-0b = A3-4 x byprod_generation_postpro_A`

`A1-0b = A1-2 x byprod_generation_Justerverk_A`

OTHER production (`A3-4`)

Even though the diagram shows a single flow, in the model this flow is disaggregated for each *Salgsgrupper* resulting from post-production (it is hence 6 outcoming flows, varying from plant to plant). The 6 flows have been calculated through Mass Balances of their corresponding *Salgsgrupper*. Although this has been adapted to each plant capabilities. E.g., the plants that cannot produce certain *Salgsgrupper* due to lack of proper technology will not produce any amount of it.

The rest of modified flows (`A0a-1, A1-2, A2-3`)

Calculated by Mass Balance of the processes they feed into.

New Parameters

`purchases_shares`

It defines from where a plant is buying each *Salgsgrupper*. This is what percentage of the Baseline Purchases of a *Salgsgrupper* is purchased from each plant. This parameter redistributes the shares while the overall amount of the purchases remains the same.

For instance, the description of one of the `purchases_shares:`

Where is `Steinkjer` buying `0504` from?

Steinkjer	Verdal	Snåsa	Selbu	Levanger	Støren
0%	72%	0%	0%	9%	19%

The table with the parameters for each Plant's purchases_shares can be found in the Supplementary documentation (excel file).

`market_participation`

It sets a reduction ratio on the internal sales of the plant with respect to the baseline values.

This parameter reduces the overall mass of products in the internal market while the distribution of the purchases remains the same.

`byprod_generation`

This parameter is set by the ratio between Produced Mass and By-products generated in the Baseline (the original quantification).

For each of the plants, there are two parameters: one for the by-products generated during *Justerverk* Processing and another for the ones generated during post-production.

Plant	`byprod_generation_`*`Justerverk`*	`byprod_generation_postpro`
Steinkjer	113%	22%
Verdal	113%	16%
Snåsa	-	49%
Selbu	113%	11%
Levanger	-	10%
Støren	113%	17%

Table 3 byprod_generation values review

`* by-product generation is >100% because the ratio is applied on the outcome of the process, not the incoming mass`

3. RESULTS

This section presents the results divided by: Outcomes of the quantification and Suggested emission-reducing strategies. The former visualizes where the wood was in the company during the studied the year 2020, e.g. the distribution, use and flow of material through Inntre Kjeldstad. It also visualizes the emissions that the Internal Trade entails. The latter describes the suggested strategies, analyses its emission reduction potential and evaluates the impacts that such shift on the company's activities would cause on the production.

3.1. Quantification of flowing Mass and emissions generated

The MFA model of the company described before allows presenting the flow of substances through the system shaped as a Sankey diagram. The chord diagrams used for the visualization of trade flows between the plants (Figure 24, Figure 25, Figure 26, Figure 27, Figure 28) have been created with the JavaScript library prepared by Amcharts (amCharts, n.d.).

3.1.1. MASS

Company level

This diagram can be found in APPENDIX 1 in a bigger size.

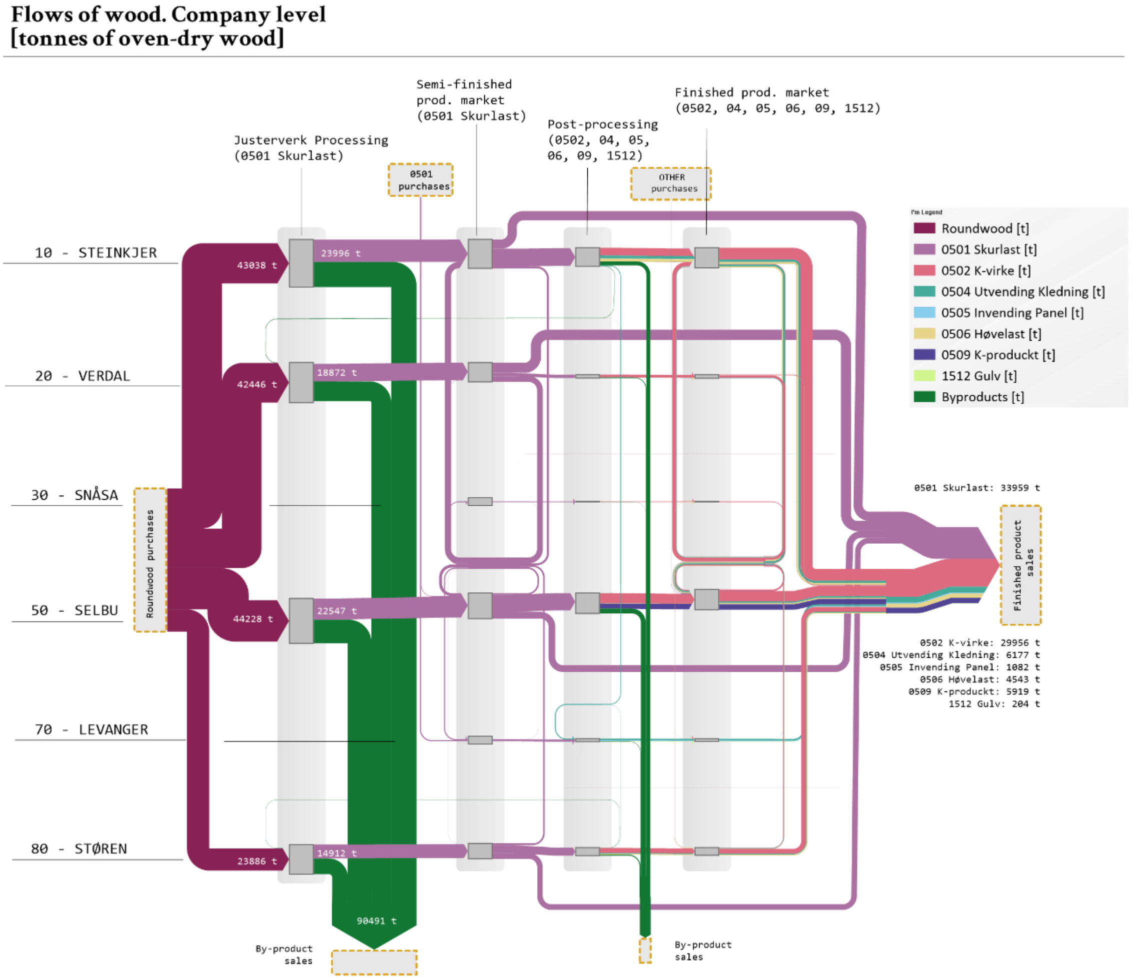


Figure 13 Mass quantification - Company level

The company bought 153.598 tonnes of roundwood, out of which 139.635 tonnes are usable wood for production after being debarked (90% of it). This wood is stored for later use in production. The use of roundwood for the year 2020 has been higher than the purchases, consuming 16.560 tonnes of the stored material. The processing of this roundwood (111% of the yearly purchases) had a 48% of production yield: 80.327 tonnes of usable primary products, e.g. 0501 *Skurlast* that can be either sold to the market straight away or post-processed. The remaining 53% are by-products that will be used either as fuel for the kilns or sold to the market in different forms.

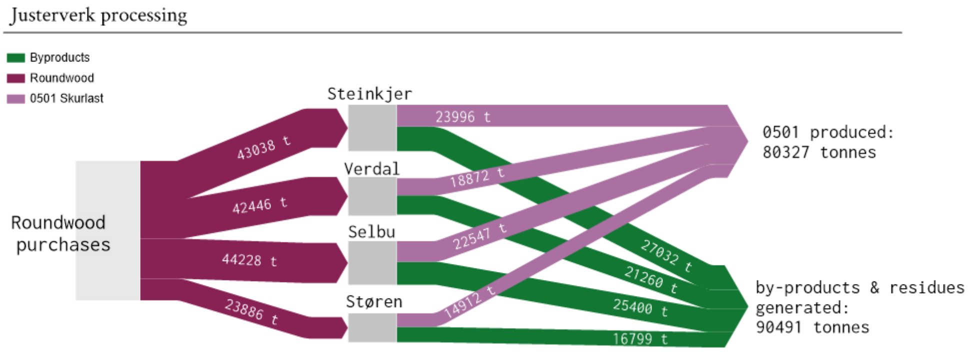


Figure 14 Mass quantification - Justerverk processing detail

The yield ratios of 0501 production (*Justerverk* process) are common to all the plants: approximately 48% when accounting for roundwood's bark, and 53% of already cleaned roundwood. On the other hand, the use of the stored roundwood varies a lot from plant to plant. While on one end Støren has used 132% of the purchased amount and decreased its stock, on the other end Verdal only used a 93% and increased its stock.

Out of this production of 0501, 33.959 tonnes were sold to the external market without any further processing (41% of the production). Along the year, the plants traded between them 12.147 tonnes of it (15% of the total production), which constitutes the first stage of the Internal Trade. The remaining 35.914 tonnes, in addition to the traded products, are combined with 1.693 tonnes of products purchased from external suppliers to be used in the production of further processed *Salgsgrupper*. To supply the demand, there has been a need to use stored 0501 from the previous year. In total, 62% of the available 0501 is used for the production of new *Salgsgrupper* and 38% is sold to the market as 0501.

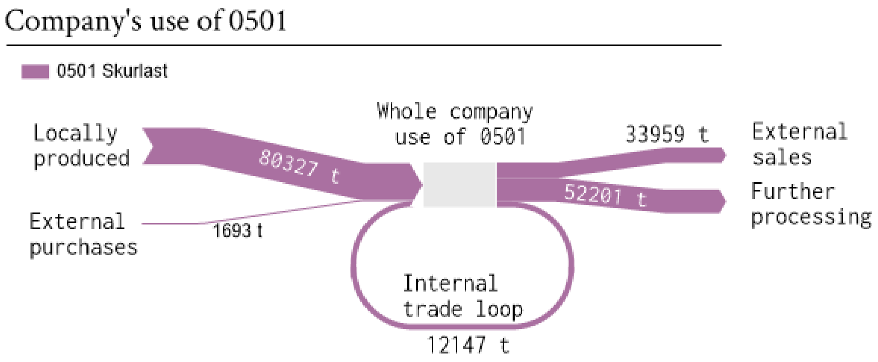


Figure 15 Mass quantification - 1st market detail

The Post-Processing of 0501 yielded a production of 44.641 tonnes of OTHER products. The transformation generated 7.562 tonnes of by-products which were mainly sold to external markets. In some plants, such as Levanger, some of them were used as fuel for the kilns. This translates as an average of 14% of by-product generation. However, the processes comprised within post-processing vary a lot from plant to plant, so the by-product generation ratio does. On one end, Steinkjer and Snåsa reach 18% and 33% respectively while on the lower end, Selbu and Levanger score a 10% and 9% of by-product generation.

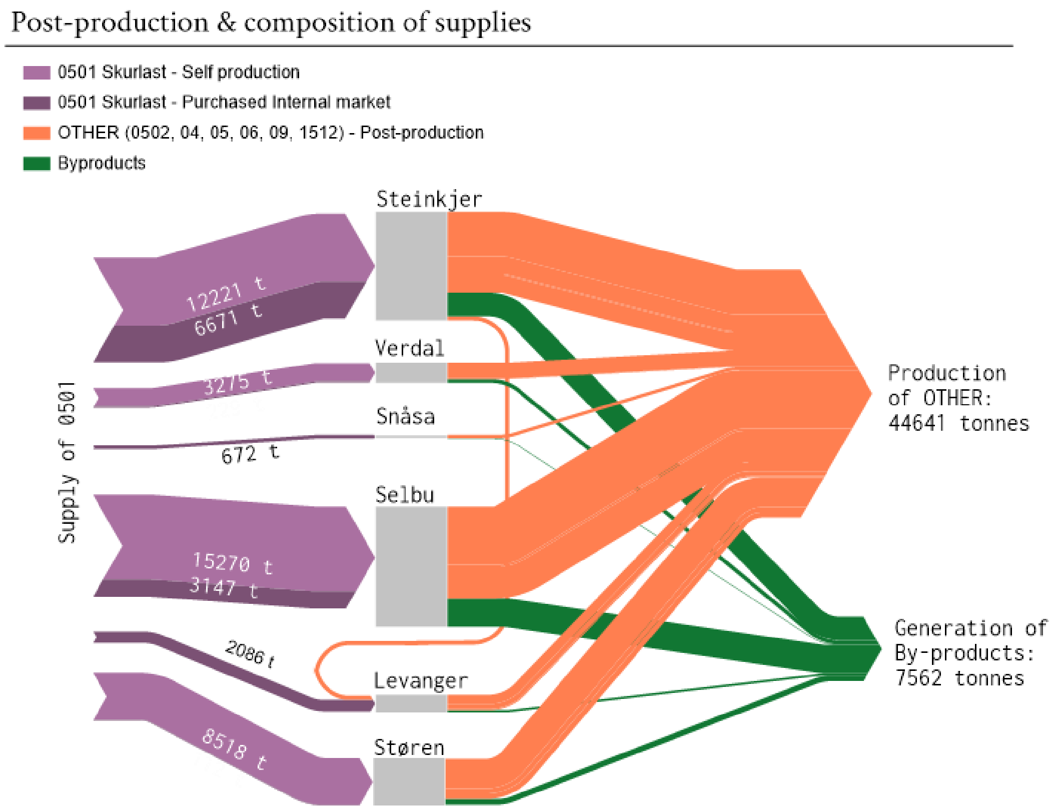


Figure 16 Mass quantification - Post-processing detail

The production split of the different *Salgsgrupper* was the following: 27.457 tonnes of 0502 *K-virke* (62% of OTHER production), 5.711 tonnes of 0504 *Utvending Kledning* (13%), 1.146 tonnes of 0505 *Innvending Panels* (3%), 4.475 tonnes of 0506 *Høvellast* (10%), 5.629 tonnes of 0509 *Limtre* (13%) and 223 tonnes of 1512 *Parkett og Gulv* (1%).

Most of this production is inputted into the Market process, except for 1.017 tonnes of 0504 (2% of total OTHER production), which were shipped from Steinkjer, Selbu and Støren to Verdal to be impregnated. Even though it is matter that does not flow through the Market process, it shall be accounted as Internal Trade which triggers emissions.

Before sending products to the External Market, the plants trade internally 10.946 tonnes of their production (22% of it). This happens due to the customer requirement of receiving the purchased products as a whole batch instead of different shipments from different facilities, and because of unavailability of materials in certain plants.

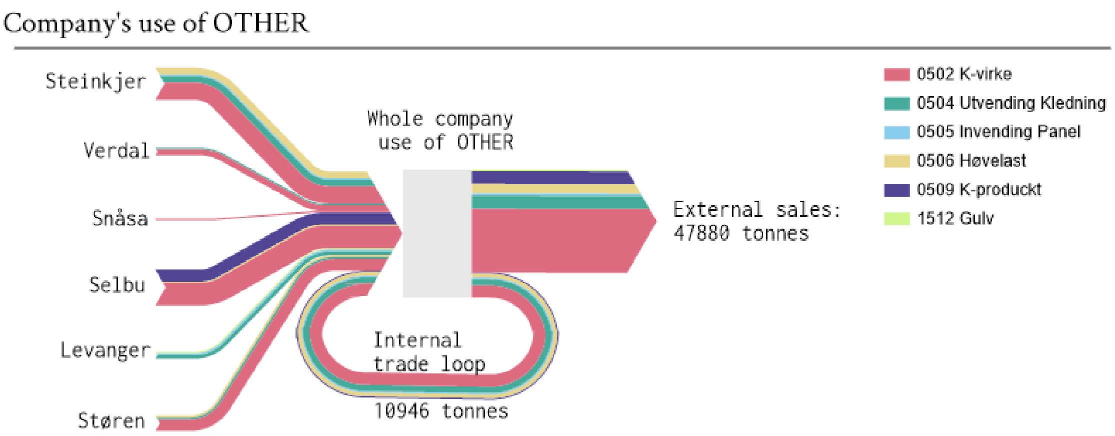


Figure 17 Mass quantification - 2nd market detail

The share of *Salgsgrupper* in this internal market is rather different from the production. Traded 0502 is a 53%, 0504 is a 27%, 0505 is just a 1%, 0506 is a 17% and 0509 is a 2%.

To supply the external demand, the production should be complemented with stored products and external purchases. The internal production contributed with 47.880 tonnes of OTHER (93% of the total external sales), 254 tonnes of 0502 and 0509 were purchased from external suppliers because the plants were not available to produce them (0,5% of total external sales) and 2.979 tonnes of products were taken from the stocks (7% from total external sales).

The external market was supplied with 81.839 tonnes of products. Out of which, Steinkjer contributes with 27.095 tonnes (33%), Verdal with 11.733 tonnes, Snåsa with 79 tonnes (0,1%), Selbu with 27.164 (33%), Levanger with 2.834 tonnes (4%) and Støren with 12934 (16%).

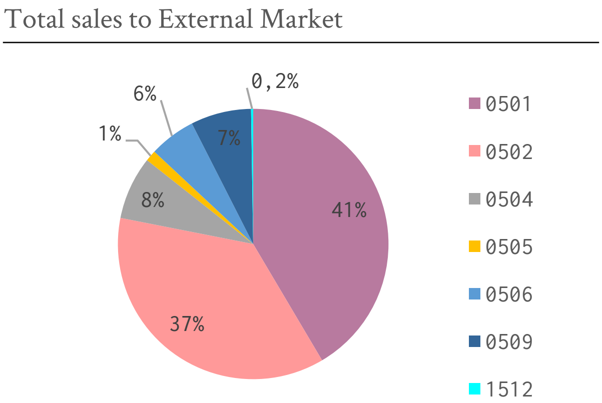


Figure 18 Shares of Salgsgrupper sold to External Market

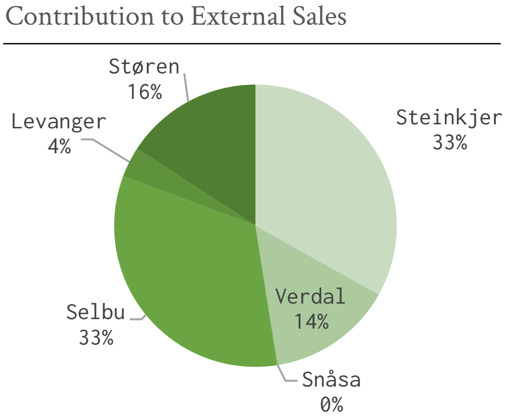


Figure 19 Distribution of sales among plants

The overall by-product and residues generation by both *Justerverk* processing and Post-Production amounts to 102.131 tonnes. This is 60% of the mass of roundwood used, while the sales of products to external market are 48% of it. This sums up 108% due to the use of products from the storages.

Internal trade

The transport of goods from plant to plant is a consequence of the different sites relying on the production of others in other to supply their corresponding demands. The first stage of the trade is the Semi-finished product's market, where 0501 is purchased externally and internally as an intermediate product to be transformed in other *Salgsgrupper*. The figure below (Figure 20) shows how each plant is participating in the internal trade of 0501. Some plants are the main purchasers in this market: Snåsa and Levanger, which are not able to produce their own 0501, purchase 700% and 1021% of the mass they put in the market. Steinkjer and Selbu are also net purchasers, with their purchases being 307% and 182% of their sales, respectively. On the other hand, Levanger and Støren are net exporters, contributing with 2709% and 1618% of what they purchase. However, even though Snåsa and Levanger are the ones with a bigger share of purchases, Steinkjer and Selbu are the main purchasers regarding total mass due to the bigger processing capacities.

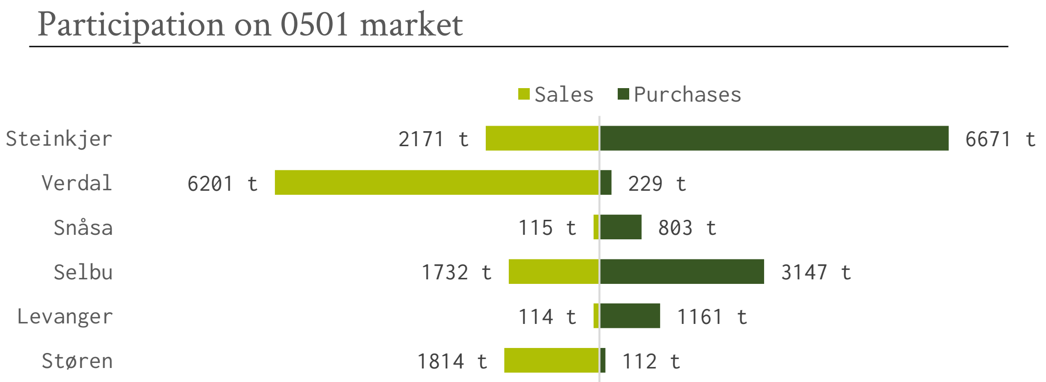


Figure 20 Plant's participation on the internal market of 0501

The figure below shows the reliance on 0501 purchases of each plant to supply their production and sales.

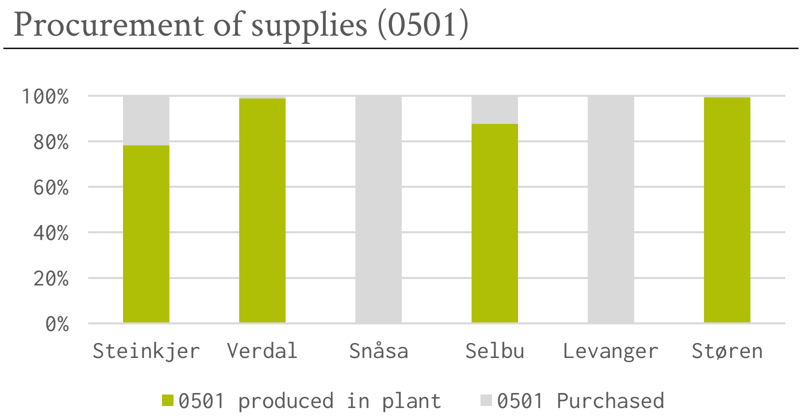


Figure 21 Reliance on purchases of each plant's post-production

The Trade of Finished products is the second group of market processes in the system. The traded mass of OTHER *Salgsgrupper* is slightly smaller than that one of 0501: 10908 tonnes are shipped between plants (10% smaller). However, it has a distribution quite similar to 0501's internal market. Verdal's selling share decreased and places Steinkjer as the main seller of products due to Verdal's focus on the production of 0501. Snåsa shifts from net purchaser to net seller, because its production is mainly used as a lightener of Steinkjer's during demand peaks.

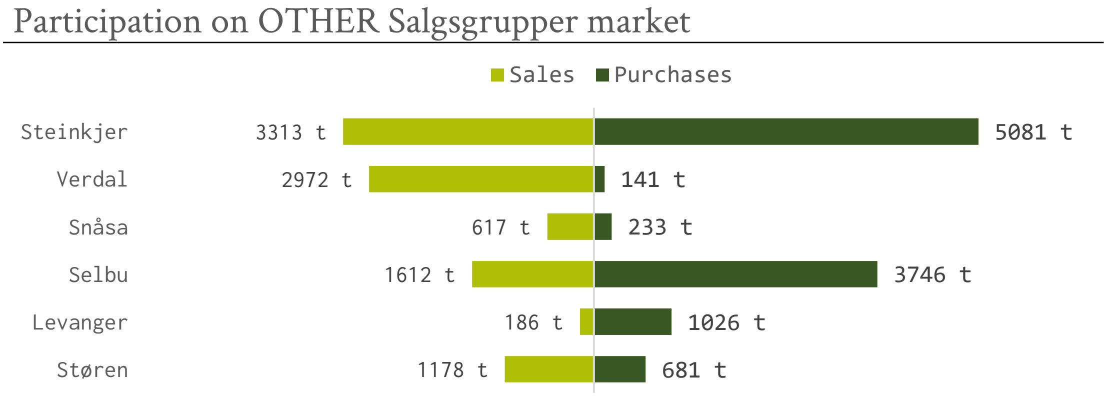


Figure 22 Plant's participation on Internal Market of OTHER

The figure below shows the reliance on OTHER purchases of each plant to supply the external demand.

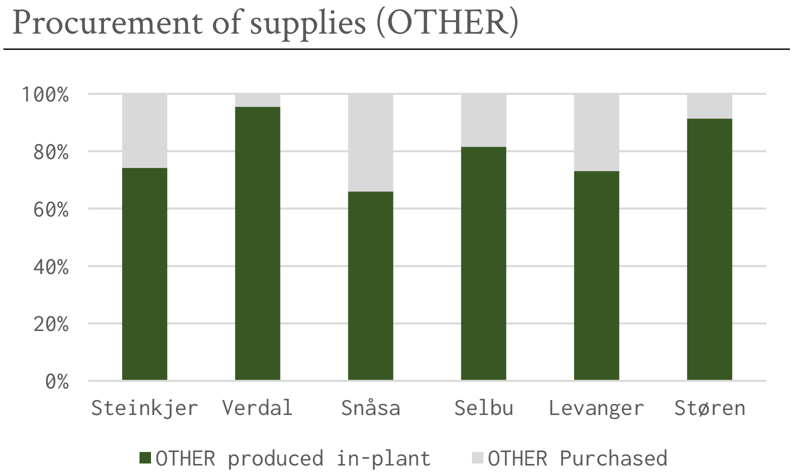
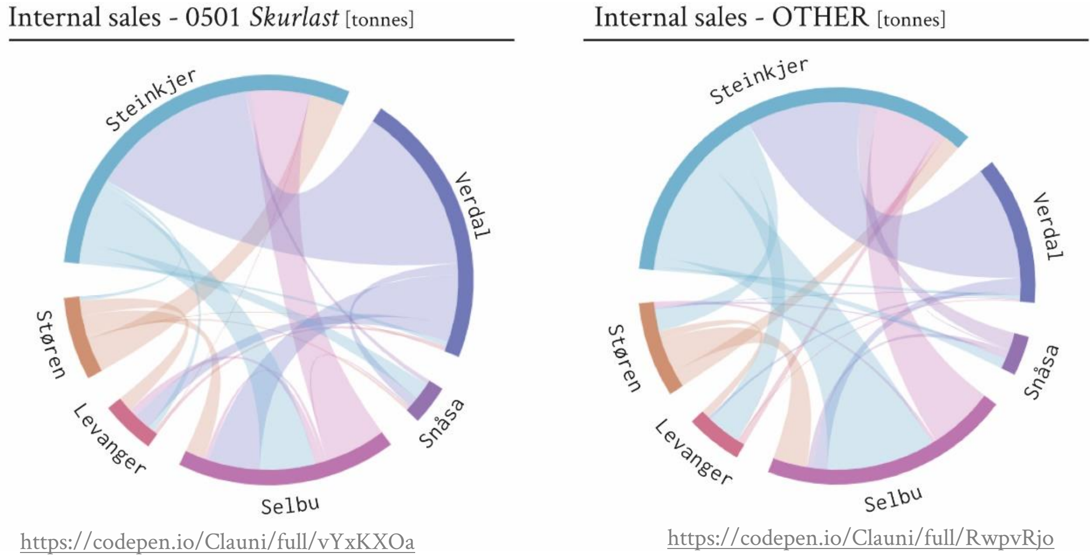


Figure 23 Reliance on purchases of each plant's External Sales

To analyse the flows from plant to plant, several **chord diagrams** are used. In these diagrams, each plant is represented by a node, placed on the outer circle. The colour of the flows indicates the seller plant and connects it with the buyer. The thickness of the flow is proportional to the mass flowing through them. An interactive visualization of the diagram can be accessed through the hyperlink next to the diagram (it is recommendable to use it because it eases quite a lot the understanding).

The following diagrams show the interactions between plants in both 0501 and OTHER markets separately.


Internal sales - 0501 *Skurlast* [tonnes]

Internal sales - OTHER [tonnes]

https://codepen.io/Clauni/full/vYxKXOa

https://codepen.io/Clauni/full/RwpvRjo

Figure 24 Traded mass on Internal markets of semi-finished and finished products (aggregated)

The biggest flow of 0501 *Skurlast* in the system is from Verdal to Steinkjer, 4.214 tonnes are sold to the latter. This flow is almost 3 times the size of the second biggest one, from Selbu to Steinkjer.

It is relevant to highlight the existence of flows that are “duplicated”, e.g. they exist in both directions between two plants. This is the trade of goods that at some point of the year has entailed transportation of some product from point A to B and at some other moment the other way around. These types of redundant flows (*Double flows*) account for 3.667 tonnes, 30% of the total internal trade of 0501.

It is also remarkable the representativity of Snåsa and Levanger in the internal trade if compared to their contribution to the overall use of 0501. They account for 7% and 10% of 0501 purchases from the internal market, while they only represent the 1% and 4% of the company’s use of 0501. This is due to the high reliance of their production on internal trade. Their lack of technology that allows them to produce 0501 drives their need for 0501 purchases. On the other end, Verdal almost does not purchase products and acts as a mere supplier for the rest of the plants. Steinkjer, Selbu and Støren rely on purchases to complete their own production.

Analysing the second market process, where the post-processed products are traded, requires disaggregating the trade flows between plants by *Salgsgrupper*. The following chord diagram still has the plants as the nodes in the outer circle, but each plant is represented by two nodes. One is an IN node, showcasing the purchases of the plant, and the other is an OUT node, showcasing the purchases. The colour of the flows represents the *Salgsgrupper* being traded according to the legend on the side.

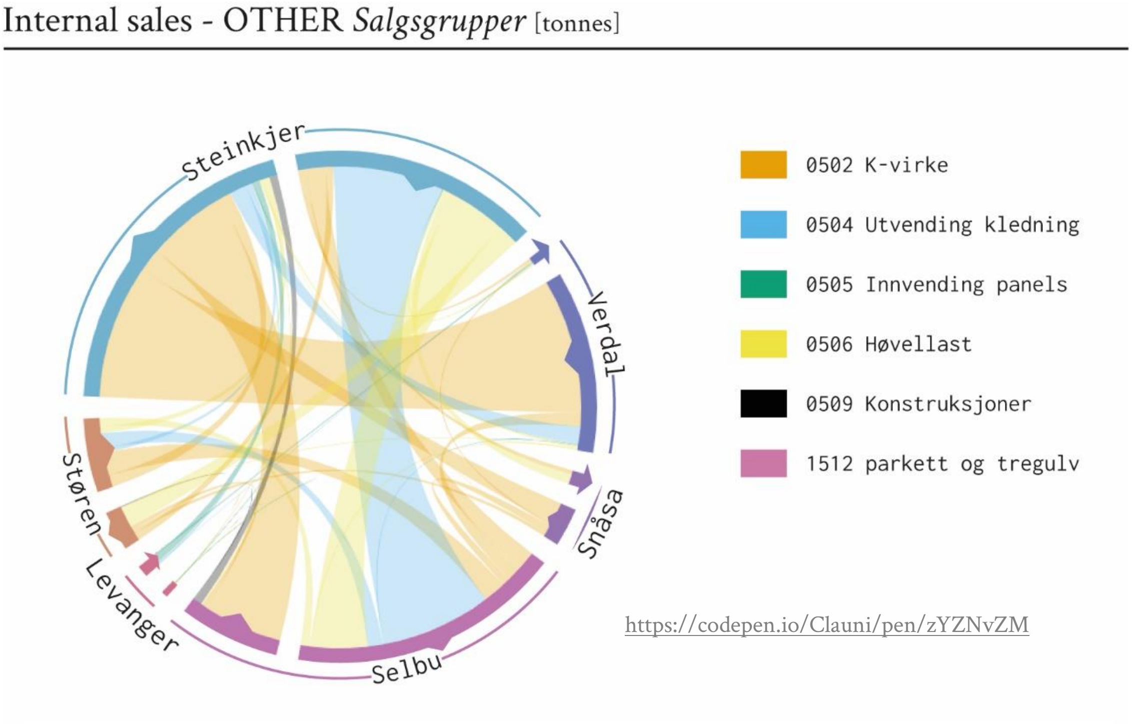


Figure 25 Traded mass of finished products (by *Salgsgrupper*)

The main traded *Salgsgrupper* in this second market is the 0502 *K-virke*: 5747 tonnes (52% of internal market trade). The second most sold *Salgsgrupper*, 2909 tonnes of 0504 *Utvending Kledning*, is roughly half of the first one's traded mass. The *Salgsgrupper* 0505 and 0509 have unique flows originated in Levanger and Selbu respectively because they are the only ones capable of that production.

This market also has *double flows*, for instance, the trade of 0502 between Steinkjer-Selbu or Steinkjer-Støren. The *Salgsgrupper* being more "double traded" are 0502 and 0506: a 22% and 18% of their respective traded mass. The share of double traded mass of the rest of *Salgsgrupper* is much lower, not rising over 9%. The *double flows* of this second market are trading 1743 tonnes, which represent 16% of the mass.

Similarly to the 0501 markets, the representativity of the smaller plants in the OTHER *Salgsgrupper* market is more significant than in the OTHER total production. In the case of Snåsa, this is a consequence of their re-processing activities; Snåsa's purchases of finished products are done to reprocess them due to specific and temporary needs of Steinkjer, instead of being aimed to supply an external demand. Levanger's production is highly focused on 0505 and since they are the only plant able to produce it, they provide the rest of the plants, which increase their participation in the market.

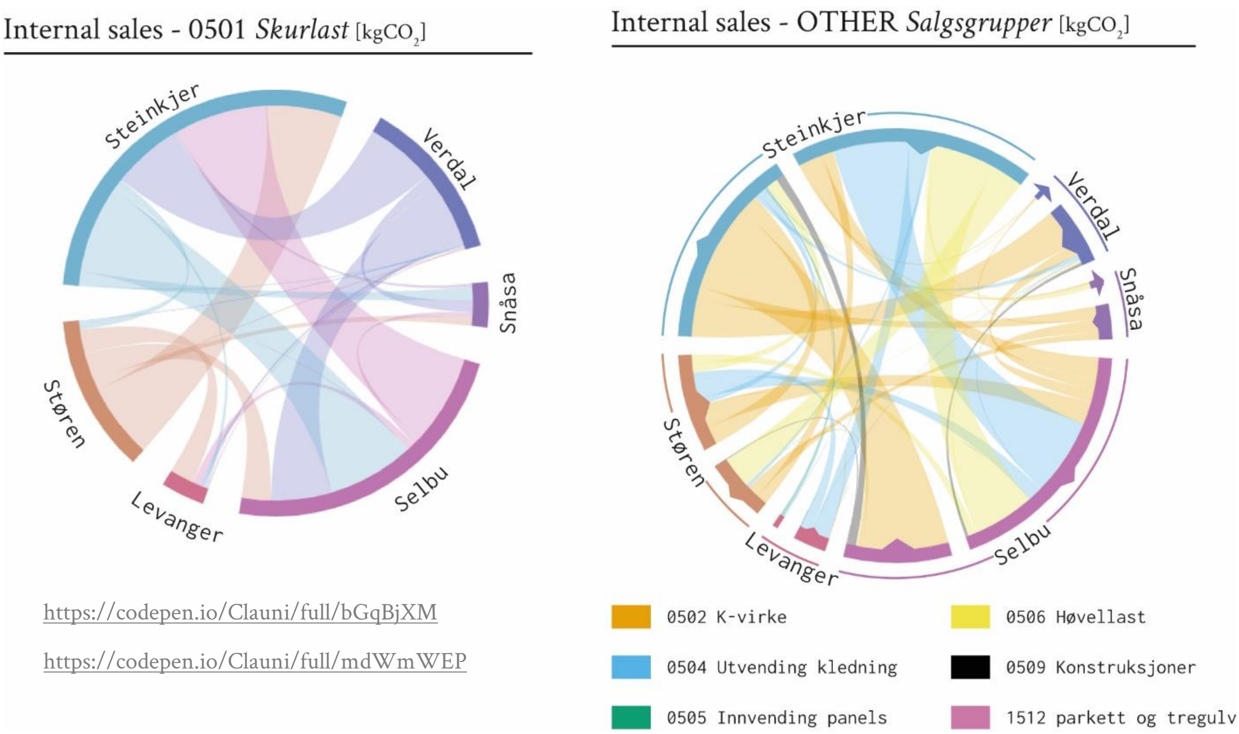
3.1.2. CO_2

The internal trade operations of the company during 2020 emitted 278,98 tonnes of CO_2 due to the transportation of 23.050 tonnes of products. The emissions generated by the 0501 markets accounted for 49,5% of the total, and the market of OTHER for 50,5%.

The emissions generated by Steinkjer purchases account for 42% of the total, and Selbu's purchases are responsible for 40%. Snåsa and Levanger, whose production relies completely on the purchases of 0501, are responsible for 8% of each of them.

The trade of 0501 is responsible for the emissions of 138 tons of CO_2 (49,5% of the total), and the trade of 0502 is responsible for the emissions of 67 tons (24% of the total).

The route with the biggest emissions is the purchases of 0501 by Steinkjer from Selbu (9% of the Company's transport emissions). It is closely followed by Selbu's purchases from Steinkjer of 0501 (8%) and 0502 (8%).



Internal sales - 0501 *Skurlast* [$kgCO_2$]

Internal sales - OTHER *Salgsgrupper* [$kgCO_2$]

https://codepen.io/Clauni/full/bGqBjXM

https://codepen.io/Clauni/full/mdWmWEP

Figure 26 Distribution of CO2 emissions by Salgsgrupper and route due to Internal trade (markets 1 & 2)

Comparison with Mass

Analysing emissions is also interesting when comparing generated CO_2 with the transported mass. Weighting the share of traded mass with the distance factor shifts the impact of plants and *Salgsgrupper* and it is a better indicator of their importance in the internal trade.

The main conclusions out of these comparisons are that 0501 *Skurlast* is being traded with closer plants than the OTHER *Salgsgrupper*. Among the finished products, 0506 is the category that is transported the longest distances. The trade with origin or destiny in Selbu and Støren is the one that entails bigger emissions, while the one flowing through Verdal is the one with the smallest impact. This is further developed and explained in the paragraphs below.

If only considering mass, the size of the market of 0501 was slightly bigger than the market of OTHER *Salgsgrupper* (53 – 47% of the total traded mass). When accounting for emissions, the distribution became the opposite (49,5 – 50,5% of the total transport emissions). This indicates a bigger distance travelled by the post-processed products, even though less mass was traded.

The weighting effect of the distances on the flows has major impacts on some of the bigger flows on each of the markets.

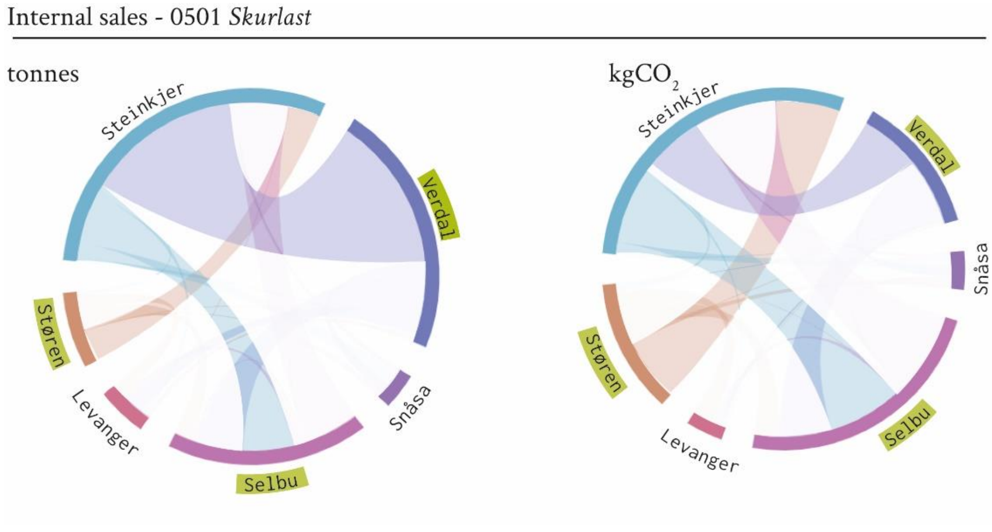


Figure 27 Comparison traded mass vs. emissions due to trade of 0501

The comparison of the diagrams for Mass, on the left, and emissions, on the right, shows how the route **Verdal-Steinkjer** decreases its share a 61% and stops being the biggest one in favour of the **Selbu-Steinkjer**, which increases 50% its share. Verdal and Steinkjer are 32km away, while Selbu is 122 km away. Similarly, the route **Støren – Steinkjer** double folds from 7% of the traded mass of 0501 to 15% of emissions (110% increase of its share).

Verdal impact on the market is greatly reduced and decreases from selling 51% of the traded 0501, to generate roughly 30% of the emissions. Selbu and Støren have similar growths, due to the larger distances to the plants in the North of the region.

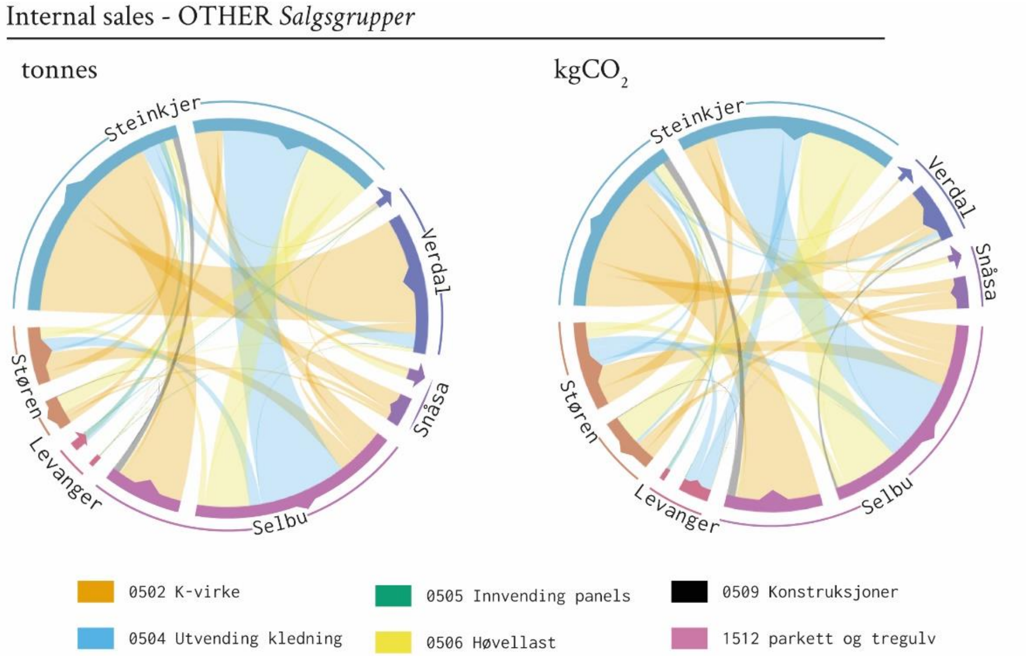


Figure 28 Comparison of traded mass vs. emissions due to trade of OTHER (Salgsgrupper disaggregated)

The analysis of OTHER *Salgsgrupper* market leads to rather similar conclusions. A big decrease in Verdal's impact, replaced by the growth of Selbu and Støren. In terms of *Salgsgrupper*, while 0502 is still the *Salgsgrupper* with the most relevance on the trade, its relevance is reduced a 9% when accounting for emissions. On the other hand, the impact of 0506 grows a 34%. This means that the 0506 products are travelling longer distances than the rest.

3.2. CO_2 emission-reducing Strategies

3.2.1. SENSITIVITY ANALYSIS (STRATEGIES 1- 3)

Strategy 1 – Double loops avoided

The Quantification of traded mass highlighted the existence of Double Loops, routes between plants that would transport certain products back and forth during the year. Even though this happens due to the plant's needs at a specific time, when addressed from a yearly point of view they are unnecessary trips.

This strategy simulates the removal of Plant A's purchases of those *Salgsgrupper* coming from a Plant B to which Plant A is also selling those certain *Salgsgrupper*.

This strategy directly reduces the mass that each plant is purchasing, subtracting the plant's baseline sales from it. This ensures that the plant will not purchase products that otherwise would be also selling.

`AX-4(050X) = baseline purchases x purchases_shares x market_participation`

In the model, this translates as reducing the `baseline purchases` while leaving the other two parameters unchanged.

Emission reduction

This strategy requires an amount of transport that generates an emission of 192,36 tons of CO_2. This is a reduction of 31% of the Baseline emissions.

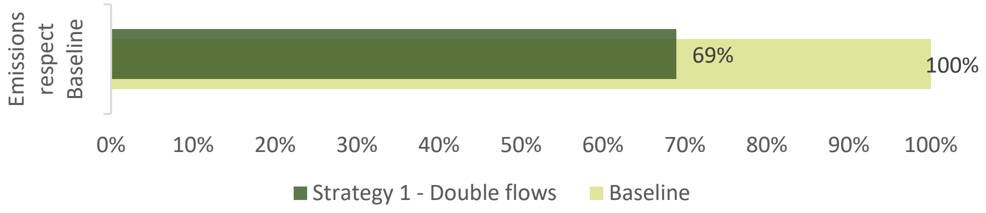


Figure 29 Reduction of emissions - Strategy 1

Impacts on production

Avoiding the *double flows* reduces the traded mass by 24%. The trade of 0501 is reduced a 30% and OTHER *Salgsgrupper* are reduced a 17%.

% VARIATION OF INTERNAL SALES

	0501	OTHER
Steinjer	-79%	-21%
Verdal	-3%	-3%
Snåsa	-	-14%
Selbu	-80%	-27%
Levanger	-	-34%
Støren	-6%	-26%

Table 4 Alteration of the sales caused by Strategy 1

The production does not suffer any modification. Since the plants stop selling the same amount that stops being purchased (the reduction on mass leaving the plant is equal to the reduction on mass entering the plant), the net amount of products in the plants remains stable.

However, reducing *double flows* has other implications. These redundant purchases are done to cover for specific necessities of a certain *Salgsgrupper* or a certain quality of product in a given timeframe (Jon Kjesbu et al., personal communication, 4 March 2021). To be able to reduce these purchases, the plants should build up a buffer of products that could be used on those occasions. This implies a bigger storage space.

As already commented on the Methodology, this study has not focused on the storage capacities of the company. However, a comparison between the stored mass and the double loops has been carried out at a monthly level to complement the analysis of this strategy. The purchased mass of each *Salgsgrupper* has been compared with the existing stock of the same *Salgsgrupper*, on a monthly basis.

The following table shows the maximum values reached during 2020:

MONTHLY PURCHASED MASS / MONTHLY STORAGE

	Steinkjer	Verdal	Selbu	Levanger	Støren
TOTAL	24%	2%	30%	21%	4%
0501	54%	2%	49%	28%	2%
0502	33%	2%	21%	62%	20%
0504	42%	15%	75888%	30%	122%
0505	2%	5%	1%	3%	0%
0506	5%	13%	98%	50%	47%
0509	22%	0%	4%	0%	44%
1512	37%	0%	0%	0%	0%

Table 5 Comparison between purchased mass and storage capacity of the plants

* Snåsa has been left out of the analysis due to the small capacity of the plant, and the temporality of their production. Whatever they buy is to be processed at that very moment, and forward it back to the seller.

Although this shows the worst peaks of the year and not the situation for every month, it can be seen how some plants would struggle if they had to create their own buffer of products.

The total amount shows how none of the plants would buy more than what they can store. However, Steinkjer, Selbu and Levanger have sensitive high ratios. If the analysis is done at the *Salgsgrupper* level, it can be seen how Selbu and Steinkjer's lack of 0501 purchases could become a bottleneck in the production by overloading their storage capacity. Similarly, Levanger would easily reach its limits, which matches with the information reported during the interviews with the plant managers (Jon Kjesbu et al., personal communication, 4 March 2021).

Selbu's high ratio for 0504 is due to the very low stock of those *Salgsgrupper*. Selbu buys 0504 to ship it directly to the customer and therefore, it does not need to store it.

Strategy 2 – Modified Purchases Shares

The Quantification of CO_2 emissions and its comparison with the ratios of traded mass yielded as a conclusion the high relevance of the choice of suppliers of each plant for their internal purchases. Flows with smaller traded mass would overtake the impacts of bigger routes when weighting them according to the travelled distance.

This strategy redistributes the suppliers of each *Salgsgrupper* for each plant on base of their distances. It prevents purchases from the two most distant plants, except for those *Salgsgrupper* that is only produced at a single site (e.g. 0505, 0509 and 1512). It also distributes the purchases from supplying plants according to their distances (the closer, the share of purchases).

This strategy does not modify the amount of internally purchased products, but it does modify where are they coming from.

`AX-4(050X) = baseline purchases x purchases_shares x market_participation`

In the model, this translates as modifying the `purchases_shares` as describe while leaving the other two parameters unchanged.

Emission reduction

This strategy requires an amount of transport that generates an emission of 200 tons of CO_2. This is a reduction of 28% of the Baseline emissions.

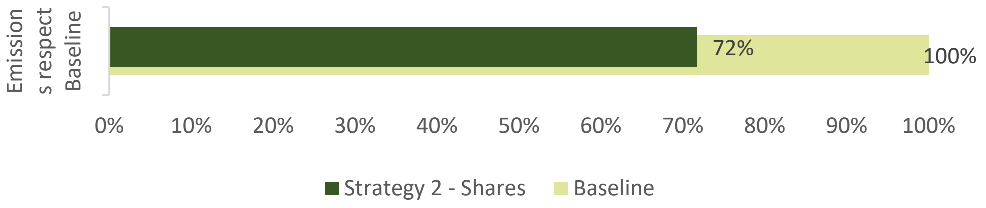


Figure 30 Reduction of emissions - Strategy 2

Impacts on production

Redistributing the purchases do not modify the overall amount of internal trade. Each plant is buying the same mass, but from different providers and/or in different ratios. This entails a different distance travelled and therefore, reduction of emissions.

Since the plants would have to cover a different internal demand, the production of each plant does change. The following table showcases the changes in their production:

% VARIATION OF PRODUCTION

	Steinkjer	Verdal	Snåsa	Selbu	Levanger	Støren
0501	-16%	29%	0%	-11%	0%	5%
0502	-5%	62%	0%	-11%	0%	-4%
0504	-25%	41%	0%	-307%	15%	64%
0505	0%	0%	0%	0%	1%	0%
0506	-36%	270%	0%	-6%	0%	89%
0509	0%	0%	0%	1%	0%	0%
1512	0%	0%	0%	0%	0%	0%

Table 6 Alteration of the production caused by Strategy 2

Steinkjer and Selbu's production are reduced, while Verdal, Levanger and Støren's increase.

This would present a challenge for several of the plants:

- Verdal declared a limit on the capacity of their driers, which would prevent them from increasing their production of 0501. Also, their technology only allows to produced rectangular profiled 0504 and 0506, which quite likely wouldn't cover the increased demand of those *Salgsgrupper*.
- Levanger declared that their production of 0504 is strongly linked to the one of 050. An increase in one entails a reduction in the other, which would quite likely prevent them from covering the increased demand.
- It would be hard for Støren to be able to supply such an increase in demand of 0504 and 0506.

Strategy 3 – Modified Market Participation

This Strategy reduces simultaneously travelled distance and traded mass by limiting the sales of the furthermost plants in the system.

It reduces the mass that each plant is purchasing from Snåsa, Selbu and Støren by 50%.

`AX-4(050X) = baseline purchases x purchases_shares x market_participation`

In the model, this translates as reducing the `market_participation` while leaving the other two parameters unchanged.

Emission reduction

This strategy requires an amount of transport that generates an emission of 215 tons of CO_2. This is a reduction of 23% of the Baseline emissions.

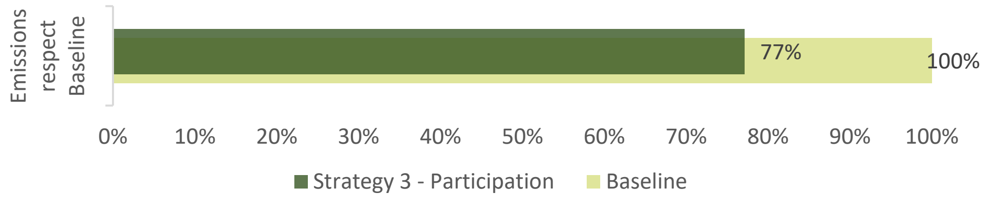


Figure 31 Reduction of emissions - Strategy 3

Impacts on production

Modifying the participation in the market of Snåsa, Selbu and Støren come with a reduction of the traded mass of 16%. Each of these plants reduces its sales to the described ratio.

	0501	OTHER
Steinjer	0%	0%
Verdal	0%	0%
Snåsa	-50%	-50%
Selbu	-50%	-50%
Levanger	0%	0%
Støren	-50%	-50%

Table 7 Alteration of the sales caused by the Strategy 3

By reducing the presence on the market of these plants, every plant has to increase its production to cover up for their decreased purchases. As shown in the following table, Verdal and Snåsa do not require any adaptation because their purchases from the targeted plants were almost inexistent.

	Steinkjer	Verdal	Snåsa	Selbu	Levanger	Støren
0501	10%	0%	0%	-4%	0%	-9%
0502	11%	0%	-51%	-4%	0%	-4%
0504	1%	0%	0%	2504%	12%	-23%
0505	0%	0%	0%	0%	0%	0%
0506	2%	0%	0%	18%	0%	-14%
0509	0%	0%	0%	-1%	0%	0%
1512	0%	0%	0%	0%	0%	0%

Table 8 Alteration of the production caused by the Strategy 3

On the other hand, this set of modifications would compromise the production of some other plants:

- Steinkjer has declared (Jon Kjesbu et al., personal communication, 4 March 2021) a shortage of roundwood as a limitation for their production. If they were to absorb these decreased purchases with their own production, they would require an extra 10% of roundwood that they might not be able to get from their typical market.
- Selbu usually buys 0504 and 0506 from Støren. This decrease in Støren's sales would require their production of those *Salgsgrupper* to increase. The extremely high ratio of 0504 is due to their usually low production (the baseline production is 5 tons, which would increase to 131 tons. It is still a rather low production compared to their typical 11.000 tons of 0502). However, Selbu's technology only allows producing a very small range of the products gathered under 0504 and 0506 Salgrsgrupper, which would probably not be enough to make up for this required increase.
- Levanger would face the same issue as the previous strategy. An increase of the 0504 production would require a decreased production of 0505, which would not allow meeting the external demand.

3.2.2. STRATEGY 4 - REALISTIC APPROACH

The analysis of the previous strategies (1 to 3) allows the comparison of their emission reduction potential with their impacts on the production. The reductions come with a required increase in the storage space and the production capacities as a trade-off, which are only acceptable below a certain threshold.

This strategy implements the above-described strategies as follows, to achieve similar emission reduction while softening the compromises:

- 20% reduction of the mass involved on *double flows.*
- Redistribution of the purchases avoiding the most distant plants but:
  - Avoid purchases of 0504 and 0506 from Verdal
  - Reduce the high demand for products from Støren
- Reduced participation in the Internal market of the most distant plants:
  - Støren = 10% reduction
  - Selbu = 10% reduction
  - Snåsa = 10% reduction

`AX-4(050X) = baseline purchases x purchases_shares x market_participation`

In the model, this translates as modifying the `three parameters` at a time, but in a milder way.

Emission reduction

This strategy requires an amount of transport that generates an emission of 187 tons of CO_2. This is a reduction of 33% of the Baseline emissions.

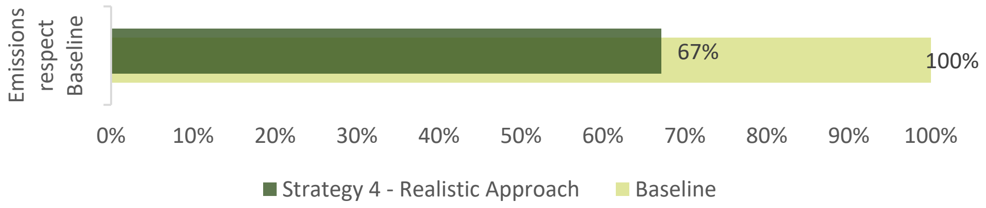


Figure 32 Reduction of emissions - Strategy 4

Impacts on production

The combination of strategies reduces the traded mass by 7%. The contribution of Steinkjer and Selbu to the internal trade decrease while Verdal and Levanger increase their share.

	0501	OTHER
Steinjer	-46%	-32%
Verdal	45%	55%
Snåsa	-	-15%
Selbu	-85%	-78%
Levanger	-	53%
Støren	-52%	16%

Table 9 Alteration of the sales caused by Strategy 4

As a result of these modifications, the production of each plant has adapted as follows:

	Steinkjer	Verdal	Snåsa	Selbu	Levanger	Støren
0501	-7%	23%	0%	-9%	0%	-4%
0502	-4%	58%	-13%	-10%	0%	-4%
0504	-2%	-3%	0%	950%	6%	-1%
0505	0%	0%	0%	0%	1%	0%
0506	-13%	-10%	0%	27%	0%	38%
0509	0%	0%	0%	1%	0%	0%
1512	0%	0%	0%	0%	0%	0%

Table 10 Alteration of the production caused by the Strategy 4

- Verdal still requires an increase in the production of 0501 that might not be feasible. However, if the external sales of this *Salgsgrupper* were to be reduced by 50%, this increase would only be of a much more accessible 12%.
- Selbu still requires increased production of 0504 and 0506 to be less dependant on Støren. However, the increase is still rather low even though the ratios are high (950% increase equates to 47 tons more. This is a 0,3% of Selbu production of OTHER *Salgsgrupper*).
- Levanger faces the same issues commented on the strategies above, but with a smaller increase.
- The increase required from Støren goes in line with the projected increased capacity declared by the plant manager during the interviews (Lars Ival Sundal & Håvard Kjesbu, personal communication, 10 March 2021), thanks to a batch of updates in their planing lines (*Høvel*).

4. DISCUSSION

This section will analyse the work previously described. Firstly, it comments on the limitations of the study and its implications for the interpretation of the results. Afterwards, the results are validated through a comparison of the findings with external sources. The acknowledging of potential weaknesses and shortcomings of the system sets the ground for a robust analysis of the results.

Lastly, a similar line of work is followed to discuss the Strategies. A description of their limitations and weaknesses leads to their interpretation, an analysis of their usefulness for the company and how to interpret them.

4.1. Limitations of the study

4.1.1. SYSTEM DEFINITION

Modelling the activities of the company entails some compromises on the level of detail that can be depicted. The scope of the study defines a boundary where some actors are left outside and not considered. Also, the assumptions taken to characterise the actors inside of those boundaries might lead to uncertainties.

Below listed are the main limitations, followed by a more detailed explanation:

> Classifying products by *Salgsgrupper* reduces the accuracy of depicting each plant's production and trade while allowing a better overview at the company level.

> Combining every by-product use and type limits the understanding of the waste generation ratios, and response to modifications on the production. However, it reduces the overall uncertainty. Better quality of data is required for such a study.

> Considering external supply and demand as a single constant agent do not provide any insight on the company's response to variations on those. Considering that one of the most relevant factors when coordinating multiple plans is the capability to balance variations on the demand of one plant without disrupting the planning of the rest (Bhatnagar et al., 1993), it would be quite relevant to extend this research toward that scope.

Inside the boundaries

The level of aggregation used to total the production disregards the subcategories of products gathered under each *Salgsgrupper*: each NOBB Hovedgrupper (main groups) is composed of several NOBB varegrupper (item group). Even though the products in each NOBB varegrupper share most of their characteristics, they have slightly different production sequences. This leads to the inability of some plants to produce all of the products listed under each Hovedgrupper. Hence, the model is not fully depicting the production capabilities of each plant. This is one of the main reasons behind the existence of *double flows* of OTHER *Salgsgrupper*.

Similarly, the production of each of the OTHER *Salgsgrupper* requires different qualities of wood, depending on whether they are structural or finishing products. These variations of wood quality are not tracked when aggregating 0501 products, and the plants need for intermediate products can only be met with certain products within the 0501 category. This is one of the main reasons behind the existence of *double flows* of 0501.

However, the aggregation level was chosen to be able to handle the amount of data at the company level, considering that disaggregating the production in NOBB varegrupper would involve over 50 different product categories instead of the 7 in use for this study.

The aggregation of every by-product in a single category entails a reduced capability of analysing the waste generation ratios. The use of by-products within the company is divided on sales and fuel for the furnaces; this study does not separate the mass by its end-use. Also, by-products generated at different stages of the production have different moisture contents, and hence different potential applications (Anerud et al., 2020; Gendek et al., 2016; Wetzel et al., 2017). On top of this, the different processes within production generate different forms of by-products (e.g. bark, sawdust, cellulose chips, dry sawdust, wood shavings…). This separation is the main differentiating factor when it comes to distinguishing by-product applications (Rentizelas, 2016; Sánchez et al., 2019), and it is not addressable from the level of aggregation used in this study. However, this choice of aggregation level is caused by both a lack of data on the amounts of by-products used as fuel and a high uncertainty on the conversion from sales data to a common unit. If the by-products are to be the focus of the study, a more accurate accounting and reporting method shall be considered at the company level, where the different forms of by-products are comparable and the real use of them is recorded.

While this study defines a clear line between intermediate products and finished products, and when are they traded, the reality of the company is more complex. Provided that the end goal of the production is to meet the demand, the assumption used by this study is just a “general rule” that sometimes is overridden if a plant needs a certain product. Some Finished products might be re-processed in the plant or in a different one, which would alter the trade patterns. This study does not contemplate a ratio for these types of mismatches, and the company has not provided any estimate.

Outside the system

There is not classification from who or where (provider or physical location) the company is stocking up roundwood and some *Salgsgrupper*. This might disregard material availability limitations from the suppliers’ side. While this study is not that relevant because the company’s interactions with external stakeholders have been considered constant, it is important to keep in mind that the company belongs to a bigger system and its purchasing patterns are sensible to the external market, and vice versa.

Similarly, the external customers of products and by-products are considered as a single pair with constant demands. While this works for the scope of this study, it would be relevant to address the impacts on the internal trade and production caused by shifts in the demand (both from geographical location and amounts).

4.1.2. QUANTIFICATION

Data sources

The data provided by the company comes from their own sales and purchasing reports, in addition to some numbers of intermediate storage and production. The data provided is already mass balance coherent on its own due to some level of data reconciliation done by the company for their reports. In addition, the modelled processes that solely rely on this type of data are mass balance consistent, which supports its robustness. Therefore, it is considered highly reliable data with a very low level of uncertainty.

However, data capture by the company entails some degree of uncertainty that shall be considered. The volume of wood is not constant during the manufacturing process; it shrinks due to variations in its moisture content and machining, being the smallest when finished (Blackwell & Walker, 2006; Schulgasser & Witztum, 2015; Šoškić et al., 2007). The reported volumes are directly calculated from the size and number of sold products. The rest of the reported values are estimations made by the company with an increasing uncertainty the further up the production chain it is located. On top of that, the volumes of roundwood are an estimation of "volume without bark", agreed between supplier and company. This is an extensively analysed topic, where the real amount of roundwood is usually reported as highly uncertain (Hohmann et al., 2017; Löwe et al., 2019; Natov et al., 2019).

The models created for this study addresses this issue by basing most of its calculations on the data reported for sales, avoiding this way most of the potential uncertainties.

Sensitivity and parameters

The process of Quantification is done based on a list of parameters applied to the data provided by the company that work either as conversion factors or transfer coefficients. Errors on these parameters are likely to disturb the quantification results and a sensitivity analysis is typically done to analyse the effect alterations of the most unreliable parameters and study their impact on the overall results.

Despite this, it has been assessed that this thesis would not benefit much from such analysis. Most of the flows in the system are based on the same conversion factor, and therefore a relative alteration of it would affect all the flows listed under Direct conversions section equally, leaving the system as it was. The only flows that would benefit from a sensitivity analysis would be the By-products generated from *Justerverk* processing; and such flows are already assessed as highly uncertain due to the data quality, the taken assumptions for their definition and the combination of parameters. Due to this, they are not a valuable outcome of this study and disturbances on their values are not relevant.

This leaves the left side of the system, roundwood purchases, stock changes, and by-products generated from *Justerverk*, as rather uncertain data. This shall be considered when analysing the results, and further study of these topics should be carried out.

4.2. Validation

Since most of the flows are quantified based on data provided by the company, the overall quantification of the system seems rather robust. In addition, mass balances of the processes and the system are consistent with errors below 1%.

However, this mass balance consistency is relative, errors might be mitigated by uncertain flows calculated via the mass balance principle.

Recovery rates vary substantially among the sawmill industry, depending on wood types, available technology or ed use of the production (Steele, 1984). Reported ratios range between 33% and 60%. According to current production standards, approximately 50-55% of volumetric recovery expected when disregarding the bark (ratio of production / clean logs) (Lennart Moberg & Urban Nordmark, 2006; Olufemi et al., 2012). These ratios only include the processes of sawing, drying and final adjusting that in this study has been considered as *Justerverk* processing. Similar numbers are reported by Inntre Kjeldstad in the documentation provided for these processes. This model reports a recovery factor of 52% without considering the bark, which is in the lower threshold of the bracket of the industry standards. This underrating could be due to an overestimated specific gravity of the roundwood, a parameter with high uncertainty. It would cause the model to consider a higher mass of roundwood than reality and report a lower yield than the actual one.

Since most of the literature does not cover the post-processing part of the sawmill operations, the only by-product generation ratios available are the ones provided by the company for the plant in Selbu. This ratio is calculated considering the processes carried out in this plant, theoretically, 11,4% of the incoming material becomes a by-product. It is important to highlight that some of these processes are not common to every plant, and therefore this ratio is not constant. The by-product generation and the production of finished products of the company after the post-processing have been assessed as low uncertainty values. However, the by-product generation of some of the plants is highly different from the expected ratios. Steinkjer and Snåsa show extremely high ratios of waste generation that indicate either a misunderstanding of the company reports or a weird behaviour on their production.

Selbu and Støren are the plants that better match the ratio. Støren by-product generation, which is below the parameter, has been confirmed with the plant manager, and it is coherent considering the lower volume of machining performed on that site.

Verdal and Støren report a slightly higher by-product generation ratio, 14% in both plants. This is unexpected for Verdal, considering that their post-production is limited to planing. Støren situation could be more acceptable due to the older technology used in the plant, as reported by the plant manager.

However, the high inconsistencies in the by-product generation ratios should be further studied and is an indicator of potential weaknesses of the model in these areas that should be revised.

4.3. Findings & novelties

4.3.1. SYSTEM DEFINITION

As shown during the introduction, the reviewed literature does not provide an accurate description of the sawmills that can be applied to the Norwegian scenario. The most accurate description can be found in Blackwell & Walker, 2006, although the linkages between processes and outcomes are better depicted by Tellnes et al., 2011, which in turn is limited to the sawing processes with no post-processing. This thesis contributes to the system understanding of this industry by showcasing the distribution of processes in 5 sawmill plants with different production lines and the capability to generate most of the solid wood construction products in the market (with the addition of glulam). This description has been generated from company data, physical interviews and plant visits.

Also, this thesis suggests a rather innovative way of depicting the interaction between sawmill plants, based on the systems created by Liu & Müller, (2013) and Singer & Donoso, (2007), that allows the focus on quantification of transport between actors while considering the manufacturing of products.

Considering the scarcity of previous applications of MFA at the company and plant level (Huang et al., 2007; Wang & Milis, 2018), it contributes to establishing the use of this tool at these details levels by showing the capabilities and benefits of such analysis. It also shows how the robustness can be boosted from the use of high-quality data provided by the studied company.

The choice of oven-dry mass of wood as a unit to quantify the system certainly leads to some weaknesses on the system due to lack of robustness on some conversion factors. However, it opens up the door to a more accurate comparison of products and by-products after transformation processes. Specific studies should be run to accurately measure the dry matter content of each by-product sold in bulk form. This analysis might be key in a future scenario where by-products are gaining relevance both in environmental and economic terms (Duchesne & Wetzel, 2003; Hall, 2002; Intergovernmental Panel on Climate Change, 2015).

4.3.2. RESULTS

The main flows of wood through the company display a strong similarity between plants, where the ratios of flow sizes look alike. This suggests that every plant is following similar production patterns, even though the analysis of the system diagram of each plant showcase rather different layouts, and this can be translated as a low specialization of the plants. The reason for this might stem from the originally individual creation of the plants (former independent sawmills) that later became part of a common company, instead of being built as parts of a whole project. This provides high adaptability to geographically variable demand because, to a certain extent, each plant is able to supply itself with the required products. While a certain degree of flexibility on the production yields the same benefits that total flexibility (e.g. every plant being able to produce everything) (Jordan & Graves, 1995), the higher flexibility, the more it hinders coordinated multi-plant planning that would yield more optimal production distributions (Singer & Donoso, 2007). This lack of coordinated planning leads to the sudden necessity for the transport of certain goods (internal transport).

Not unexpectedly, the relevance of by-product generation during sawmill operations is again highlighted by the results. Furthermore, thanks to broadening the scope of the study so it also includes the post-processing of sawn products, it becomes clear the importance of by-products generated in this second step. It is also remarkable the added relevance of accounting for these by-products due to their dry nature, which makes them much more suitable for bioenergy generation (Anerud et al., 2020; Wetzel et al., 2017).

The trade patterns are rather similar in both markets. This is an unexpected result provided that the cause for the trade in the two production stages is different. The trade of 0501 is triggered by the need for semi-finished products to post-process. On the other hand, trade in the secondary market arises from the need to supply external demand from products that the plant is not able to produce (except for Snåsa and Levanger that mainly purchase to re-process and absorb peaks of demand in other plants).

However, in both markets the purchase of products can be translated as either:

- a technology limitation that causes the plant to not be able to produce what it is buying
- a lack of throughput that causes a shortage of what it is buying

By looking at the reliance on the markets of the plants, it can be seen that Verdal and Støren do not rely on purchases, while also mostly contributing. The opposite happens in Selbu and Steinkjer. This indicates that Verdal and Støren are producing to supply other plant's external demand.

Provided that the production of 0501 in Selbu is already on its limits, it can be assessed that its situation of net importer is hardly solvable just by production planning. On the other hand, Steinkjer has not reported such limitations and therefore it is likely that there is a gap for improvements there.

The most traded category of the OTHER *Salgsgrupper* is 0502 *K-virke*. All the plants involved in these flows have the technology to produce it, and therefore it is a matter of throughput that is potentially solvable by coordinated planning among the plants.

The analysis of trade has also highlighted the existence of *double flows* between plants, which mostly happen on 0501 trade. Even though one of the reasons for their existence is the unpredictability of the raw material, which may yield different qualities of wood than what each plant requires for its production, it would be important to assess to which extent they stem also from lack of combined multi-plant planning.

The most straightforward solution for the *double flows* would be increased storage that allows absorbing the variations on the wood quality. While currently this might be an expensive or inviable solution, future scenarios such as increased carbon taxes (Andersson, 2019; Santos, 2017) or limitations on the road freight transport availability as a consequence of national regulations disincentivising certain routes (Klima- og miljødepartementet, n.d.) should be considered and could increase the profitability of such investments.

The quantification of CO_2 has been done by first quantifying the amount of transport via tonne-kilometre, factorized by an emission intensity factor associated with the mean of transport. This quantification of the transport allows other analysis by differently factorizing the tonne-kilometre, for instance in economic terms or number of trucks used.

Quantified amounts of transport and emissions are disaggregated by plant and *Salgsgrupper* and therefore can be used to update the EPDs created by the company. Such EPDs (APPENDIX 2) either do not contemplate this inter-plant transport within their declarations or assume a standard amount of transport to an inexistent central warehouse to comply with the reporting methodology. Therefore, they could well benefit from a more accurate approximation of tonne-kilometre per cubic metre for each type of product.

However, the total amount of CO_2 quantified due to internal transport is rather small when compared with the net CO_2 uptake of the raw materials transported and it is not likely affecting the global warming potential quantified in the EPDs. Therefore, the limited impact can be foreseen due to taxations on CO_2 emissions of the products.

4.3.3. USABILITY

Besides the innovativeness commented above, this analysis has also potential usefulness for the company. Although some pieces of the knowledge above presented is certainly already known by the company provided that it is based on their data, the **combination of quantifications and visualization** in a common framework is presented as a novelty. Planning at the company level benefits from data visualization, allowing easier communication and understanding between members of the company (Cybulski et al., 2015; Eppler & Platts, 2009).

This analysis also has highlighted the potential relevance of increasing the definition of the data captured regarding by-products. Currently, only sold amounts are reported and in a hardly comparable units' system. The company would benefit from a better accounting system for its by-product generation. Although they already control the lumber conversion factor achieved by their production, by tracking which type of by-product is generated, sold to the market, and used as fuels for their kilns they could better assess their participation in growing markets.

Overall, this description of one of the most relevant sawmill companies in the Trøndelag region contributes to building a systemic understanding of the sawmill industry in the area and can be used to build a robust description of the regional sawmilling activities. This goes in line with the Fylkeskommune plans of boosting the bioeconomy of the region through innovation and value creation(Trøndelag Fylkeskommune, 2017) that relies on a deep knowledge of the available resources and interconnections between industries.

4.4. Strategies

4.4.1. LIMITATIONS

The modelling of the strategies is focused on the study of flows that entail physical transport from plant to plant, and it is limited to the internal factors that affect them within the company. This choice of scope disregards the impacts arising from variations on actors outside of the company, such as the variability on the supply's availability or the external demand. Accounting for these factors is key for the success of the production (Baghalian et al., 2013). Roundwood availability is expected to either stay constant or increase, hence not threatening the production. By contrast, the external demand for sawn and engineered wood products is hardly predictable in the short term (Marcy Nicholson, 2021) and growing in Europe in the long term (FAO, n.d.), which would add pressure to current production. Therefore, it is of high relevance to expand this study to include external actors.

This model uses the same System Definition as the model used for the quantification and uses ratios and data derived from it. Because of this, it inherits the limitations commented in section Limitations of the study. A remarkable drawback of this is the lack of accuracy on the modelling of by-products generation which has hence been not included in the assessment of the results.

Also, the change of the stocks has been set to zero. This means that the balance of stored products remains constant after a year of operations, neither grows nor decreases. It is assumed that the plants would still use their storage capacities, but these fluctuations will not be tracked due to a shorter duration than the time scope defined. However, inventories are a key asset of an organization (Goyal & Gupta, 1989) and as such, they should be addressed in a more in-detail study.

The strategies are laid out as a method to try and reduce the use of transport and the CO_2 emissions along with it. Therefore, the CO_2 emission reduction is only approached through a net reduction of the total tonne-kilometre. This disregards other emission reduction strategies that would rely on modifications of the emission intensity, such as electrification of the transport means (electric fleet of trucks and vans) or shift towards the use of biofuels.

4.4.2. FINDINGS

The analysis of the individual effects of each of the strategies (strategies 1 - 3), and the combined effect of them all simultaneously (strategy 4), yields as a conclusion that reducing the *double flows* and redistributing the purchases, so the plants buy from nearby plants are the best strategies.

The reduction of *double flows* equates to a modification of the management of the stocks of each plant. By a different use of the storages, the plants would be able to reduce their eventual needs for specific products or product qualities and the use of transport related. This can be achieved, not only by increased storage space but also by reassessing the type of products using this space and their fluctuations along the seasons. The safety stocks shall be adequately sized to ride out the issues generated by a variable demand without overproducing (Croston, 1972).

The comparison of monthly purchases and stock sizes done during the analysis of strategy 1 highlights the potential overloading of stock capacity for certain product categories, while the overall capacity of the plant is always in a safer situation. This suggests that the utilization of the storages could be optimized, prioritizing the piling up of sensible product groups such as 0501.

The redistribution of the purchases entails a different organization of the production at the plant level, which equates to a re-assessment at the company level of the production volumes of each product category for every plant, e.g., modifying how much of everything is each one producing. Here it enters in the discussion phasing out of certain production lines, the installation of new technologies, or the investments in upgrades for certain lines. These topics need a much more thorough study since they entail many other implications.

However, some relevant ideas can be drawn from this study to contribute to such discussion. If the reduction of transport for internal trade is to be reduced through shortening the purchasing routes (buying from the closer plants):

- Verdal would intensify its role as a semi-finished products provider in the system. This would require increased drying capacities in the plant.
- Levanger would face a higher demand of 0504 and 0505 production. Currently, this is not feasible due to the capacity limits of their painting line, and the not interchangeability in the use of the line (a higher production of one category requires a direct equivalent reduction of the other).
- Støren would face a higher demand of 0506. This would likely reduce the production strain in Steinkjer, and this could balance the demand in Levanger commented in the previous point.

As a general conclusion of the points above, the production at the company level shall be reassessed in a way that all plants optimize their production according to coordinated multi-plant planning, instead of focusing on supplying their own demand. This conclusion goes in line with other plant optimization analyses (Singer & Donoso, 2007).

The model is set in a way that ensures the production of enough products to supply 2020's external demand. This is done to study how different could the behaviour of the company could have been during that year and be able to compare the results with a baseline. It is relevant to consider how the external demand is a given parameter for each of the plants, assuming this way that each of them has an individual market to supply. This has been done this way to focus the research on the internal transport of the company, disregarding its interactions with external actors. A rather different approach would be to consider the whole external demand as a total amount to supply, allowing each plant's contribution to differ from the baseline. This is a systemic difference and understanding the external demand at the company level would allow better multi-site coordination, yet it would involve considering geographical distribution of the customers (it would not make sense to supply customers located in the far north with products from Støren, located in the south if other solutions are also possible).

The quantification of CO_2 emissions has yielded a smaller result than expected, already commented in previous sections. The emissions are not only dependant on the distance and mass transported. They can also be reduced by a lower emission intensity of the chosen transport. The promotion of zero-emission mobility alternatives such as electrification or the use of hydrogen is contained in Norway's Transport plan (Samferdselsdepartementet, 2021). The production and supply chain of second generation biofuels is highly interlinked with sawmill and forestry industries (Cambero et al., 2015; Pettersson et al., 2015). This reduction in the emission intensity of road freight transport can therefore be expected to occur shortly. This raises the question of whether trying to reduce the emissions through a reduction in the use of transport is even relevant and beneficial, considering that some of the previously suggested interventions to reduce transport might also entail certain emissions (whether it is by purchasing new machinery or enlarging storage spaces).

However, the use of internal transport has other implications for the company besides the CO_2 emissions that can be analysed based on the quantification of tonne-kilometre by replacing the emission intensity factor with one that depicts, for instance, economic impact. This would allow again to compare whether the intervention to reduce transport is worthy for the company.

4.4.3. USABILITY

It is important to highlight that this set of strategies is not meant to be implemented by the company but to be used as a complementary assessment on their discussion about the topic. This thesis only analyses some of the factors concerning the internal transport in Inntre Kjeldstad. Some of the factors left aside have been commented on in the Limitation sections. Some others are not even within the scope of this type of MFA, for instance:

- Social aspects such as the implications on the required workforce that such modifications could have, or the know-how that implementation of new production lines could require.
- Vested interests within the company or in the region. Each plant is in a different Kommuna, which could have different expectations from the company. Also, other companies coordinate with Inntre Kjeldstad to sustain their production.

What actually can be done with the model is, now that the system is defined, and the framework is been built to depict the interactions between each plant's production, it can be redefined to include external actors (external demand and supply), simulate impacts on the plant's production by implementing new technologies, or study by-product generations once the accuracy of the conversion ratios is improved.

5. CONCLUSIONS

The increasing relevance that the wooden building materials are gaining in the market thanks to its climate change mitigation potential and the innovative applications for the by-products generated while processing them, combined with the importance of the sawmill industry in the Trøndelag region creates a need for a better system understanding about this industry in central Norway. This would contribute to a more robust assessment of the forestry industry in the region, which is vital for the bioeconomy boosting plans of Trøndelag fylkeskommune. Previous studies of the sawmill industry have considered it as a single plant process, are limited to the primary sawing of roundwood and usually quantifying its production in volume.

This thesis has performed a Material Flow Analysis of the oven-dry mass of wood through Inntre Kjeldstad, the biggest multi-plant sawmill company in Trøndelag. The production of the company has been depicted by analysing the system definition of each of the plants that comprise it and combining them into a simplified system that gathers the main transformation processes (*Justerverk* processing and Post-processing), and the trade of goods between the plants and with external actors. This provides a much more detailed picture of the operations and allows a better analysis of the products, sorting semi-finished and finished products. It also allows separating the by-product generation by production stages, which is strongly related to the moisture content of them and defines their potential applications. The system has been used to quantify the production and the by-product generation that it entails and to analyse the transport of products between plants in an Internal Market of semi-finished and finished products. This analysis has also provided a quantification of the related CO_2 emissions.

A second model of the system has been developed to simulate four transport-reducing strategies and to analyse their impacts on the production of each plant. This analysis has shown that a reduction in the use of transport is achievable but has some implications. It requires a re-assessment of the management of storages to avoid the sudden need for certain goods, that creates redundant routes (*doubles flows*), and it requires a redistribution of the production, strengthening the trade between nearby plants. Overall, the main conclusion is that, if the use of transport (and emissions generated) is to be reduced, the production of the plants shall not be optimized individually but in a coordinated way, creating a balance between all the plants.

Although, the study has focused only on the inside operations of the company, disregarding suppliers and external demand. This has set a strong limitation on the analysis, which would highly benefit from being able to assess the variability on the demand. Especially when it comes to describing the impacts of modifications on the trade of finished products, highly affected by the customer location. Also, the study has achieved a rather low certainty level on the quantification of the by-products, which would require an in-depth study of the conversion ratios to be able to accurately sort and quantify them in a disaggregated way.

All in all, the goals of this study of creating a more defined description of the functioning of a sawmill and depicting the internal connections of a multi-plant company from an MFA approach are well reached. It is a robust body of work that can be built upon. Whether it's a regional study, a production planning tool, or a wooden house.

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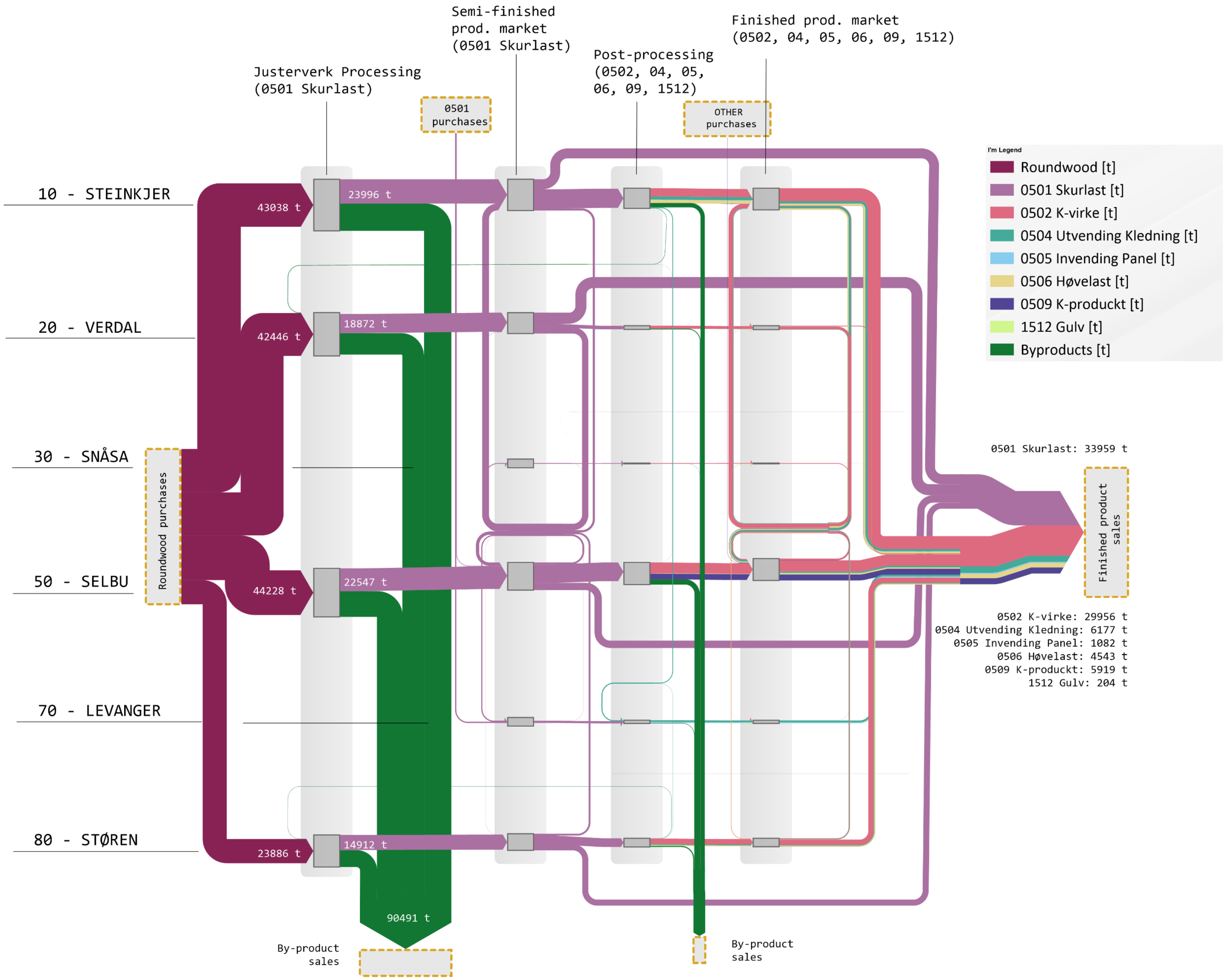
APPENDIX 1

Quantification - Company level

Flows of wood. Company level [tonnes of oven-dry wood]



APPENDIX 2

Kjeldstad Trelast EPDs

ENVIRONMENTAL PRODUCT DECLARATION
in accordance with ISO 14025, ISO 21930 and EN 15804

epd-norge.no
The Norwegian EPD Foundation

Eier av deklarasjonen — Treindustrien
Utgiver — Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonens nummer — NEPD-309-180-NO
Godkjent dato — 09.03.2015
Gyldig til — 09.03.2020

Heltrepanel av bartre til innvendig bruk
Produkt

Treindustrien
Eier av deklarasjon

Treindustrien

epd-norge.no
The Norwegian EPD Foundation

ENVIRONMENTAL PRODUCT DECLARATION
in accordance with ISO 14025, ISO 21930 and EN 15804

Eier av deklarasjonen: — Kjeldstad Trelast AS
Programoperatør: — Næringslivets Stiftelse for Miljødeklarasjoner
Utgiver: — Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonsnummer: — NEPD-1384-455-NO
Publiseringsnummer: — NEPD-1384-455-NO
ECO Platform registreringsnummer: — -
Godkjent dato: — 05.09.2017
Gyldig til: — 05.09.2022

K-bjelken

Kjeldstad Trelast AS

www.epd-norge.no

KJELDSTAD

ENVIRONMENTAL PRODUCT DECLARATION
in accordance with ISO 14025, ISO 21930 and EN 15804

epd-norge.no
The Norwegian EPD Foundation

Eier av deklarasjonen — Treindustrien
Utgiver — Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonens nummer — NEPD-308-179-NO
Godkjent dato — 09.03.2015
Gyldig til — 09.03.2020

Konstruksjonsvirke av gran og furu
Produkt

Treindustrien
Eier av deklarasjon

Treindustrien

Miljødeklarasjon ISO 14025 / ISO 21930

epd-norge.no

KOBBERIMPREGNERT TRELAST
Klasse AB (for bruk over bakken)
Impregnert med Wolmanit CX-8

NEPD nr: 87 N

Treindustrien

Verifikasjon

Deklarasjonen er utarbeidet av:
Catherine Grini, SINTEF Byggforsk

PCR

Om EPD

Figur 1

Informasjon om produsent

Interesseorganisasjon — Treindustrien

Informasjon om produktet

Omfang — vugge til port

Produksjonssted — Norge
Markedsområde — Norge

Miljøindikatorer

Global oppvarming	33,2 kg CO₂-ekv.
Energibruk	1 999 MJ
Andel fornybare materialer	99 %
Inneklimaklassifisering (iht. EN 15251:2007)	Ikke relevant

Produktspesifikasjon

Sammensetning sluttprodukt — Tabell 1

Materialer	Enhet	Mengde	Andel (%)	Datakvalitet
Høvellast	m³	1,00	99 %	Spesifikke data
Wolmanit CX-8	kg	5,50	1 %	Spesifikke og generiske data

ENVIRONMENTAL PRODUCT DECLARATION
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Eier av deklarasjonen — Treindustrien
Utgiver — Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonens nummer — NEPD-310-180-NO
Godkjent dato — 09.03.2015
Gyldig til — 09.03.2020

Utvendig kledning med vanntynnbar maling
Produkt

Treindustrien
Eier av deklarasjon

Treindustrien

ENVIRONMENTAL PRODUCT DECLARATION
in accordance with ISO 14025, ISO 21930 and EN 15804

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Eier av deklarasjonen — Treindustrien
Utgiver — Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonens nummer — NEPD-307-179-NO
Godkjent dato — 09.03.2015
Gyldig til — 09.03.2020

Skurlast av gran eller furu
Produkt

Treindustrien
Eier av deklarasjon

Treindustrien

EPD-1384-455-K-Bjelke-og-K-Stender.pdf (kjeldstad-trelast.no)

EPD-Innvendig-Panel-085N-rev1.pdf (kjeldstad-trelast.no)

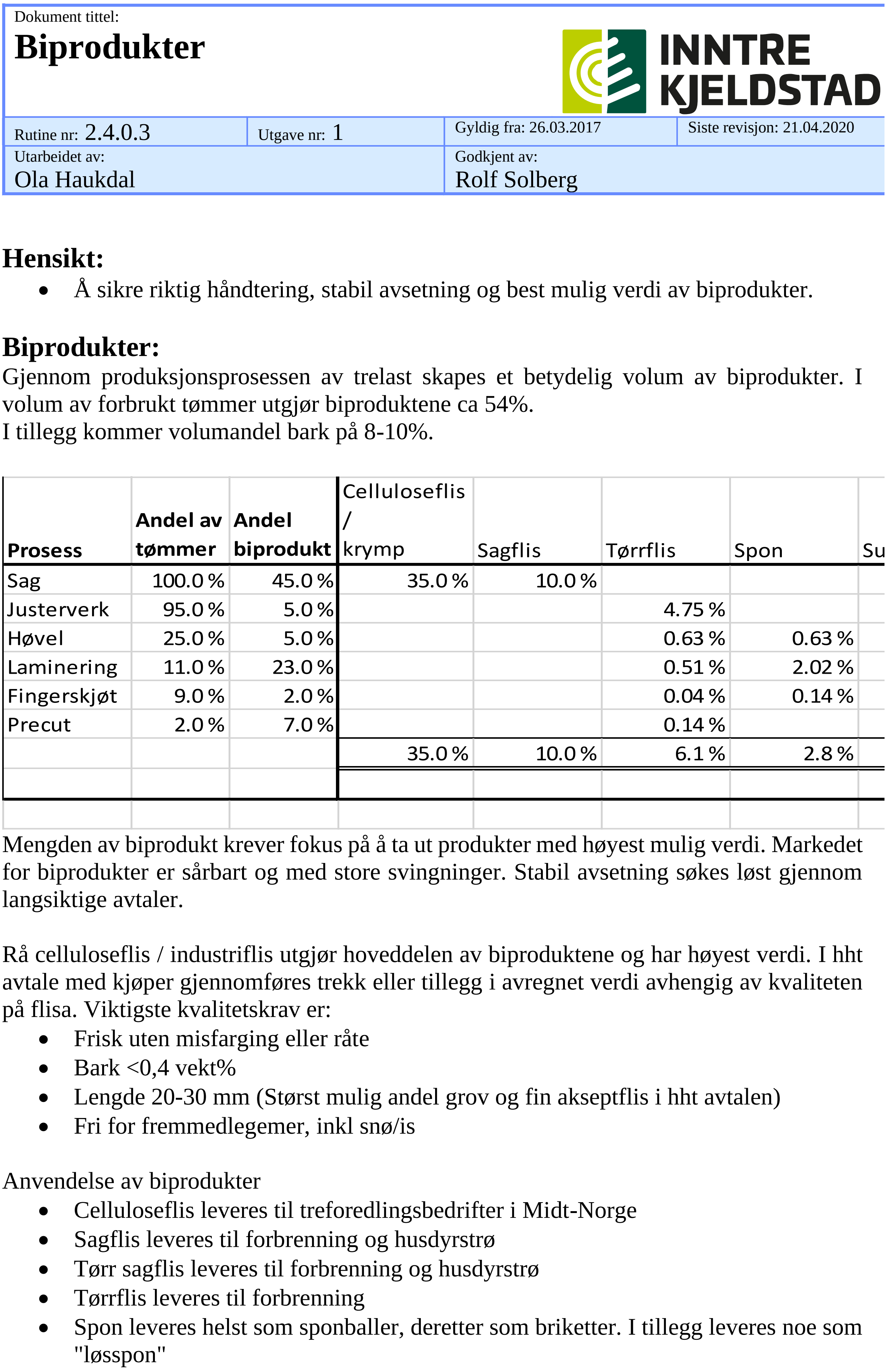
EPD Impregnert virke_Wolmanit_vugge_til_port.xls (kjeldstad-trelast.no)

EPD-Malt-utvendig-kledning-137N-rev1.pdf (kjeldstad-trelast.no)

EPD-Norsk-konstruksjonslast-084N-rev1.pdf (kjeldstad-trelast.no)

EPD-Norsk-Skurlast-082N-rev1.pdf (kjeldstad-trelast.no)

APPENDIX 3 INTERNAL DOCUMENTATION



Dokument tittel:
Biprodukter

INNTRE KJELDSTAD

Rutine nr: 2.4.0.3
Utgave nr: 1
Gyldig fra: 26.03.2017
Siste revisjon: 21.04.2020
Utarbeidet av:
Ola Haukdal
Godkjent av:
Rolf Solberg

Hensikt:

- Å sikre riktig håndtering, stabil avsetning og best mulig verdi av biprodukter.

Biprodukter:

Gjennom produksjonsprosessen av trelast skapes et betydelig volum av biprodukter. I volum av forbrukt tømmer utgjør biproduktene ca 54%.
I tillegg kommer volumandel bark på 8-10%.

Prosess	**Andel av tømmer**	**Andel biprodukt**	Celluloseflis / krymp	Sagflis	Tørrflis	Spon	Su
Sag	100.0 %	45.0 %	35.0 %	10.0 %			
Justerverk	95.0 %	5.0 %			4.75 %		
Høvel	25.0 %	5.0 %			0.63 %	0.63 %	
Laminering	11.0 %	23.0 %			0.51 %	2.02 %	
Fingerskjøt	9.0 %	2.0 %			0.04 %	0.14 %	
Precut	2.0 %	7.0 %			0.14 %		
			35.0 %	10.0 %	6.1 %	2.8 %	

Mengden av biprodukt krever fokus på å ta ut produkter med høyest mulig verdi. Markedet for biprodukter er sårbart og med store svingninger. Stabil avsetning søkes løst gjennom langsiktige avtaler.

Rå celluloseflis / industriflis utgjør hoveddelen av biproduktene og har høyest verdi. I hht avtale med kjøper gjennomføres trekk eller tillegg i avregnet verdi avhengig av kvaliteten på flisa. Viktigste kvalitetskrav er:

- Frisk uten misfarging eller råte
- Bark <0,4 vekt%
- Lengde 20-30 mm (Størst mulig andel grov og fin akseptflis i hht avtalen)
- Fri for fremmedlegemer, inkl snø/is

Anvendelse av biprodukter

- Celluloseflis leveres til treforedlingsbedrifter i Midt-Norge
- Sagflis leveres til forbrenning og husdyrstrø
- Tørr sagflis leveres til forbrenning og husdyrstrø
- Tørrflis leveres til forbrenning
- Spon leveres helst som sponballer, deretter som briketter. I tillegg leveres noe som "løsspon"

NTNU
Kunnskap for en bedre verden