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Plate rolling mill flow development

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Levyvalssaamon virtauksen parantaminen

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Työn tarkoituksena oli määritellä matalaan aihiovarastotasoon liittyviä tuotannonsuunnittelun vaikutuspiirissä olevia levytuotannon virtausta rajoittavia ongelma-alueita. Tämän tavoitteen saavuttamiseksi oli tutkittava laajasti levytuotannon eri vaiheita. Keskeisenä aiheena oli tuotannon suunnittelutoimintojen ja itse tuotannon kattava tutkiminen ja mallintaminen. Työn empiirisen osion perustana olivat lukuisat henkilöhaastattelut, tuotantodatan tulkinta sekä informaatio- ja materiaalivirtojen havainnollistaminen. Työssä myös pyrittiin nostamaan tuotannonsuunnittelun kykyä tunnistaa havaittuja ongelmia varhaisemmassa vaiheessa.

Ongelmien tunnistamiseen käytettiin Lean-työkaluja. Visuaaliset havainnollistukset tehtiin Microsoft Excel ohjelmalla ja Draw.io kaavionpiirustusohjelmalla. Levyvalssaamon virtauksen kannalta oleellista kyky suunnitella ja priorisoida sellaisia sulatuksia, joiden sisältöjen leikkaustapakohtaiset osuudet tasapainottavat parhaiten toisiaan. Sillä tavalla suunnitelluista ja priorisoiduista sulatuksista on nykyistä paremmat edellytykset luoda sellaista valssausjaksoa, joka aiheuttaa nykyistä vähemmän ruuhkaa. Yhdeksi johtopäätelmäksi saatiin, että *oikean* tuotannon ja tekemisen merkitys korostuu matalan aihiovarastotason aikana. Tuotannonsuunnittelun kykyä myötävaikuttaa virtaukseen voidaan nostaa. Merkittävimpiä kehitysehdotuksia ovat sulatuksien priorisointia helpottavien suunnitteluohjelmistojen lisäosat ja uuden toimintamallin luonti valssausjakson suunnitteluun. Työssä käytetyt tutkimusmenetelmät soveltuvat yleisesti tuotantolinjoille ja prosesseille. Tulokset itsessään ovat tuotos tietyn ajankohdan ja tuotantoketjun tilanteesta eivätkä siksi sovellu yleiseen käyttöön.

Asiasanat: Lean, Tuotannonsuunnittelu

ABSTRACT

Plate rolling mill flow development

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University of Oulu, Degree Programme of Mechanical Engineering

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Supervisor(s) at the university: Jari Larkiola & Jari Niskanen

The purpose of the work was to define problem areas in terms of the flow of plate production that are within the scope of production planning during the times of low slab level. In order to achieve this goal, the aim was to study the different stages of plate production. Taking into account the production planning operations and the production itself from the steel plant to the plate rolling mill was an essential topic. Numerous personal interviews, interpretation of production data and illustrating information and material flows were the basis of the empirical work. The work sought to identify problems and produce relevant additional information to support the production planning.

Lean tools were used to identify the problems and the visual illustrations were made with Microsoft Excel and the diagram drawing software Draw.io. One conclusion is that during the times of low slab level, the importance of prioritizing the *right* production is emphasized. Production planning's ability to contribute to production flow can be enhanced. The ability to plan and prioritize strands whose contents in terms of cutting routes best balances each other. Strands planned in this way are in a better position to create a rolling cycle that causes less congestion. The most significant improvement suggestions are add-ons for the planning software, which help production planning to prioritize the *right* strands and a new operating model for the sequence planning. The working methods are generally applicable to production lines and processes. The results themselves consist of the output from this particular point in time and the specific situation in the production chain; therefore, they are not applicable for general use.

Keywords: Lean, Production planning

PREFACE

The purpose of this master's thesis work "Plate rolling mill flow development" was to define problem areas associated with the flow of plate production that are within the scope of production planning. The thesis was completed at SSAB Raahe for the production and delivery management department between November 2021 and April 2022.

I would like to thank SSAB Europe Oy for entrusting me with this very wide-ranging thesis topic. Perceiving and evaluating the whole process of plate production was a truly enriching experience. I believe that there is still room for improvement in this intriguing area. However, I hope that the work will contribute to improvements in the current situation.

Many people deserve to be recognized and commended for their contributions to this work. Thanks to the production workers, work management, development engineers and production managers who participated in the personal interviews. Special thanks to the supervisors at the factory, plate rolling mill development engineer M. Sc. Harri Halonen and production control manager Ville Virpiranta.

As I conclude my studies at the University of Oulu, I would like to express my gratitude to my fellow students, with whom I have had unforgettable experiences. I also thank my family and especially my mother, who has supported me in my studies over the years. Final thanks to my dear girlfriend who helped me somewhat keep my sanity when momentary challenges felt overwhelming.

Oulu, 15.06.2022

Janne Tihinen
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1 INTRODUCTION

1.1 Research background

The subject for this thesis first came up in the factory's internal SOP workshop. At first there were questions related to planning and executing plate mill production plans in different loads and production situations. Different organizations from production planning to production itself have recognized problems related to low slab level. Goals for the thesis are to specify low slab level-related problems throughout the plate mill's production chain and produce valid information for production rough-design and define ways to recognize emerging problem situations earlier. The thesis is also based on the assumption that the desired production load is feasible. The focus of the thesis is finding solutions and defining problems under production planning's influence. The final goal for the thesis was to produce improved practices for SSAB Raahe's production planning organization.

1.2 Conducting research and structure of report

The theoretical part is presented at the beginning of the report and provides an overview of the methods used for problem identification and theory, which lay the groundwork for the main subjects of the research. The main themes are Lean (also SSAB One), production planning, levelling production and visual illustrations of information and material flow. A significant portion of the information obtained comes from personal interviews.

2 SSAB EUROPE OY - RAAHE

SSAB Europe is one of SSAB's three divisions among SSAB Special steels and SSAB Americas. Tibnor and Ruukki Constructions are SSAB's subsidiaries. SSAB Europe is a leading Nordic-based steel producer of high-quality strip, plate and tube products. SSAB Europe's production plants tailor products to customer needs by working closely with customers and understanding their needs. SSAB Europe has two main categories of premium products: advanced high-strength steels (AHSS), which are sold globally to the Automotive industry; premium steels, which are sold in the European market to other industries. In 2020, SSAB Europe reached 3.3 million tonnes in steel shipments. The number of employees was approximately 6700. SSAB's main production facilities are located in Raahe and Hämeenlinna (Finland) and Luleå and Borlänge (Sweden). Steel making processes are integrated as blast furnaces and steel plants are located on the same site. SSAB Europe's steel mills have an annual crude steel production capacity of 4.9 million tonnes (SSAB, 2021).

SSAB Raahe has a long tradition as a producer of high-quality steels. Raahe is one of SSAB Europe's facilities which produces high quality hot rolled strip and plate products. Annual production capacity is up to 2.6 million tonnes, of which strip production consists of 2 million tonnes and plate production 0.6 million tonnes. SSAB Raahe employs around 2500 people. The original steel factory in Raahe, called Rautaruukki, was established in 1960. The first blast furnace was completed and production of iron began in 1964. SSAB and Ruukki merged into one company in 2014 (SSAB, 2018b).

3 LEAN TOOLS AND THEORY

Lean is a well-known operating philosophy. For some, the word means using certain methods, while for others Lean is a strategy that covers all the work done in an organization. It can be said to be a holistic approach or a long-term strategy for managing operations that encompasses corporate culture, values, policies, methods, employee participation in leadership, etc. The House of Toyota is one basic graphic representation to define the original Toyota Production System (TPS), which is the foundation of Lean. The structured wholeness of operating principles for Toyota, the TPS, was created in the late 1940s by Taiichi Ohno with the support of Eiji Toyoda. The House of Toyota is presented in Figure 1. The house conveys stability, the twin pillars of JIT and Jidoka support the roof, representing the final goals. The operational stability of TPS is provided at the base by other Lean concepts such as Heijunka, standardization and Kaizen. Just-in-time, Kaizen, Heijunka, Jidoka and other Lean-related concepts are discussed below. Similar graphs with minor changes are presented in numerous sources discussing Lean. However, the primary message stays rather the same (Petersson *et al.*, 2018).

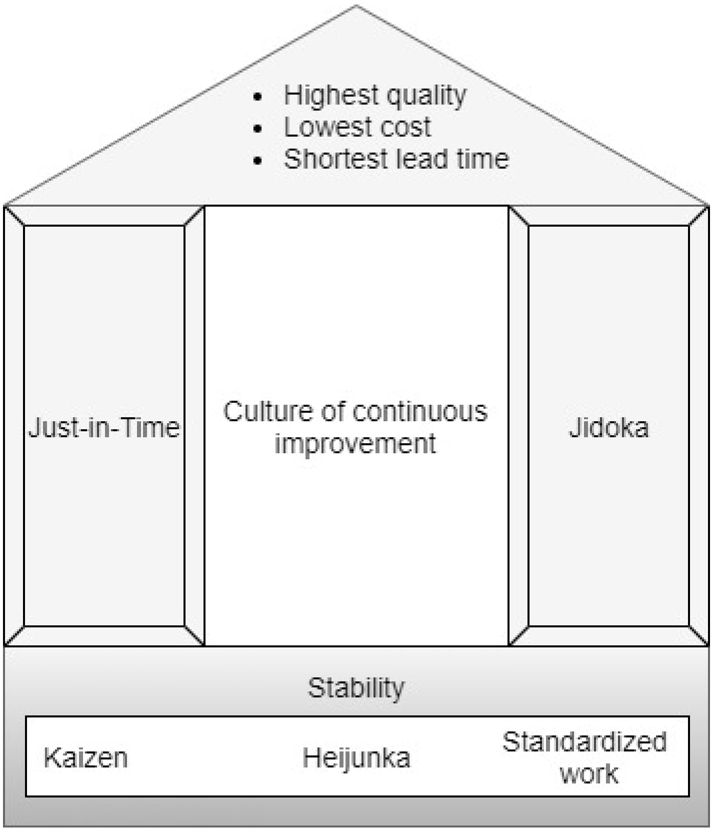


Figure 1 The house of Toyota (Modified from sources: Krajewski, Malhotra and Ritzman, 2016; Petersson *et al.*, 2018).

Lean is a set of management practices, which is about moving ever closer to uninterrupted flow in the sequence of operations that deliver flawless quality. Flow considers services and products; in addition, it considers information and designs necessary to run operations. This requires continuous improvement in three sections (Bicheno and Holweg, 2016):

- Waste reduction
- Value enhancement
- People involvement

Every system, regardless of the management method, needs good results in order to continue its operations. Petersson *et al.*, (2018) present two managing methods to direct operations: Management by means (MBM) and management by results (MBR). MBM is called a management method based on commonly agreed procedures and methods. The opposite is MBR, which is more result-orientated and the ways and methods to achieve results get less attention. Results are essential for both methods. The difference is the way the results are achieved. A characteristic feature of a result oriented approach is that they tend to focus more on the metrics which have a direct financial link. Management is seldom interested in *how* the work is done. The results of the metrics are more significant than the ways the work is done. Management is often focused on launching new work instructions and following the metrics. If the targets are not met, it is not uncommon to launch radical changes to achieve the targets. Naturally, in MBR the work is done by specified methods, but they are not selected in the same systematic way as the MBM methods.

Management by means differs significantly from MBR. The manager's focus is on the method/mindset level and not on the result-oriented level as in MBR. In MBM, the selected work methods have a clear connection to the company's values and principles. After the management have verified the fitness of the working methods, it focuses on ensuring that the whole organization follows the given direction. A fundamental aspect of MBM is that small but steady progression brings more performance improvements than large-scale and revolutionary changes in the short-term. Successful MBM requires loyalty to selected working methods, continuity, interest in directing operations and the ability to ask the right questions from employees. In practice, no operation is led purely by the other method, but if the goal is to pursue Lean, the MBM approach is most likely an advantageous managing method (Petersson *et al.*, 2018).

3.1 Elements of the House of Toyota

Some of the key elements of the House of Toyota are presented in this chapter. One of the most popular systems that incorporates the generic features of Lean systems is the just-in-time (JIT) system. JIT philosophy is a belief that waste can be eliminated by cutting unnecessary capacity or inventory. JIT represents operations that maximize the value added by each of a firm's operations by removing waste and delays from them. Lean systems deal with eight types of waste or "muda". The eight types of waste that often occur in firms disproportionately and which must be eliminated by implementing Lean systems are:

1. Overproduction. Manufacturing item(s) before a true need. This makes defect detection difficult and creates excessive lead times and inventory.
2. Inappropriate processing. Using high-end equipment and materials and sacrificing extra time and resources to create something the customer is not ready to pay for.
3. Waiting. Time is considered as wasted when an item is not being moved or processed. Long production runs, poor material flows, and processes that are not linked one to another can cause over 90 % of a product's lead time to be spent waiting.
4. Transportation. Unnecessary movement and material handling of the product between process steps may cause defects and deterioration of product quality without adding customer value.
5. Motion. Excessive effort related to human movement like reaching, bending, walking, etc., should be redesigned.
6. Inventory. Inordinate inventory hides problems on the shop floor, impedes communication and increases lead times. Work-in-process inventory is a direct result of overproduction and waiting.
7. Defects. Quality defects add superfluous costs in the form of rework, scrap handling, rescheduling, increased inspection, a loss of customer goodwill and lost capacity.

8. Underutilization of employees. Inadequate use of employees' knowledge and creativity. This is a failure of the firm and it inhibits long-term efforts to reduce waste (Krajewski, Malhotra and Ritzman, 2016).

The goal of the Lean system is to eliminate eight types of waste, thus, produce services and products only as needed, and to continuously improve the value-added benefits of operations.

3.1.1 Jidoka

Jidoka is a Lean method that is widely adopted in manufacturing and product development. It is also known as autonomation. Jidoka strives to ensure that the product's quality meets the expectations of customers by applying two main principles: built-in quality and stopping when an error occurs. Jidoka also represents a visual management system, whereby the statistics on the safety, quality and performance of the system in relation to the targets for a given fabrication cell or production line is clearly visible to workers at all times (Krajewski, Malhotra and Ritzman, 2016). Basically, Jidoka is all about learning. If a function has a clear target to locate and fix errors so that they do not repeat, it is natural to be interested in why things are not going as well as they should (Petersson *et al.*, 2018).

3.1.2 Heijunka

Heijunka is one foundation of Lean, which means levelling. In Lean, it refers to the levelling of the production load by both volume and product mix. Instead of manufacturing large quantities of one product, the products are made in smaller batches. The principle of levelled scheduling is straightforward but the requirements to put it into practice are quite severe, although the benefits can be remarkable (Slack, Chamber and Johnston, 2004). Thorough planning is a prerequisite for high flow and recourse efficiency, and it also provides favourable working conditions for employees. Thus, levelling is one of the base elements of the Lean design. Levelling can be performed from two aspects: levelling pieces and levelling workload (Petersson *et al.*, 2018).

3.1.3 Standardization

Standards, on the other hand, describe the best known and mutually agreed way of doing certain tasks. A standard is valid until a new, better way is found and accepted together.

The standard may not be excellent, but it sets the current way of doing a task. Organization-wide comprehension of the role of standards is essential. Most of all, standardization is vital in terms of locating deviations, increasing predictability and enabling learning.

3.1.4 5x-Why

Decreasing waste is essential in Lean. However, a common issue is finding the deviation's root cause to prevent it from happening again. 5 Whys is a systematic method to map the root cause of a deviation. It is an iterative process, where the question "Why?" is asked after an explanation again and again. Usually "Why?" is asked more than five times, hence the name of the tactic. Iterative process leads one closer to root cause(s), but as the questions continue, it might become more challenging to form causes and new questions (Petersson *et al.*, 2018).

Bicheno and Holweg (2016) present some guidelines for more effective use of 5 Whys:

1. "People" reasons are not acceptable. Usually the root cause is in the system, not in the people. One should ask "Why do people behave the way they do?".
2. Keep the tone of the questions and statements neutral. Don't allow Whys to become accusing or personal.
3. At each step, prioritize. There may be several reasons, but choose one or two that are most significant.
4. Keep focus on probing the real root causes and clarify them. There is a risk of widening out the reasons. In other words, a risk of extending the reasons beyond reasonable boundaries.
5. Stop when you get to a reason that is beyond your control. The analysis can get on and on.

3.2 SSAB ONE

SSAB has its own management philosophy which includes vision, values and principles. SSAB ONE has many commonalities with Toyota management philosophy referred to as Lean, but SSAB ONE is based on SSAB's own history and perceptions. The vision is a stronger, lighter and sustainable world. Three values in SSAB ONE are creating value for the customer, bearing responsibility (respect for people) and exceeding expectations.

There are four principles which specify the way in which the above principles are pursued. The four principles are: for the customer, normal state, right from me and learn and develop. The first principle, “for the customer” emphasizes the mindset that the work flow can be streamlined. This has similarities with Lean JIT. The focus should be on production flow efficiency rather than resource efficiency. The second principle, “normal state”, means establishment and standardization of working habits and creating a stable basis for operations. “Normal state” defines standardized working habits, state of equipment and cleanliness, normal state for work flow, i.e. levelling and normal state of performance, i.e. essential metrics. The third principle, “right from me” emphasizes the prevention of errors in production. The fourth principle, “learn and develop” states that everyone is responsible for developing their own work. SSAB ONE presents the same eight types of waste presented above in chapter 3.1 (SSAB, 2022).

3.3 Factory physics

3.3.1 Variability

Variability is any kind of deviation from the optimum process that produces perfect quality on time, every time. There are two types of variability: internal and external. Variability could be stated as a polite term for problems. Usually, managers seek to remove or decrease variability, thus, it also removes waste (Heizer and Barry, 2011). External causes can be defined as those which a firm has the least amount of control over such as its external customers and suppliers, who can periodically cause disruptions. Internal causes are considered a firm’s own operations that can be the culprit in what becomes the source of continuous disruption in the chain (Krajewski, Malhotra and Ritzman, 2016).

Krajewski, Malhotra and Ritzman (2016) define supply chain disruptions in more detail. They have listed the following external causes: environmental disruptions, supply chain complexity, loss of major accounts, loss of supply, customer-induced volume changes, service and product mix changes, late deliveries and underfilled shipments. The listed internal causes are the following: internally generated shortages, quality failures, poor supply chain visibility, engineering changes, order batching, new service or product promotions, and information errors.

3.3.2 Kingman's equation

In 1961, British mathematician John Kingman developed an equation (1) describing a relationship between waiting time (cycle time in queue, i.e. CT_q), variability (V), utilization (U) and processing time (T) for a single process centre.

(1):

$$CT_q = VUT, \tag{1}$$

there is also the industrial engineering version of the Kingman equation.

(2):

$$CT_q = \frac{({C_a}^2 + {C_e}^2)}{2} + \left(\frac{u}{1-u}\right) t_e\ , \tag{2}$$

where ${C_a}^2$ = squared coefficient of variation of interarrival times (indicator of demand or flow variability), ${C_e}^2$ = squared coefficient of variation of effective process times (an indicator of process variability), u = utilization (fraction of time when a workstation is not idle for lack of parts) and t_e = effective process time (time required to complete a job including downtime at a process centre).

One classic graph of the theory is presented in Figure 2, which basically illustrates the content of the Kingman's formula. Mildly simplified, Kingman showed how throughput time depends on resource utilization and amount of variation. The higher the variation, the longer the throughput time (if resource efficiency is kept constant). The higher the resource efficiency, the longer throughput time unless the variation can be reduced. The shape of the curve is nonlinear as the figure shows. Kingman proved that the system is very sensitive to the effects of variation, especially when resource utilization is high (Pound, Bell and Spearman, 2014). To summarize, if a firm pursues to have a reasonable lead time or queue length, the following are useful. Achieving 100 % utilization is a disadvantage. Reduction of variation should be strived for, as lower variation allows operation with lower inventories. The Lean idea of levelling the production also aims to reduce the variation to obtain faster lead times and other benefits (Roser, 2022).

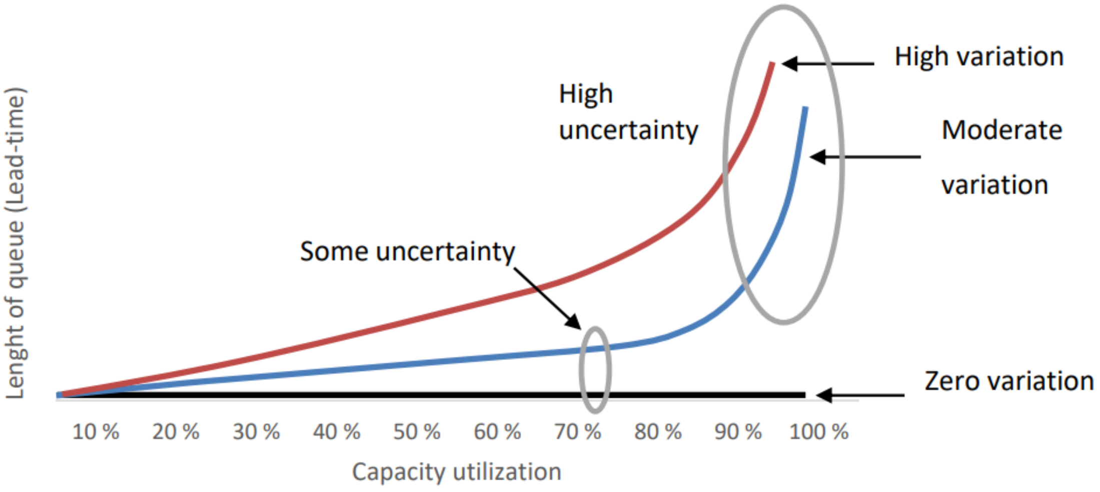


Figure 2 Illustrative graph of the Kingman's equation.

Six Sigma's define, measure, analyse, improve and control (DMAIC) methodology typically focuses on the reasons for variability which increase the requirements for buffers. If there were no variability, demand and transformation would be in perfect synchronization, yielding maximum profit and cash flow. However, there is always some sort of variability. In the presence of variability, buffers are required to synchronize demand and transformation. Nonetheless, if the revenue generated by an increase in variability exceeds the costs of the commensurate buffering increase, increasing variability is profitable (Pound, Bell and Spearman, 2014).

3.3.3 Buffers

Because transformation and demand cannot be perfectly synchronized in the presence of variability, buffers are required. A buffer is an excess recourse that corrects for misaligned demand and transformation. Buffers are like shock absorbers; they absorb temporary changes caused by some variation. There are three kinds of buffers:

1. Inventory. Extra material in the transformation process or between it and the demand process.
2. Time. Any kind of delay between a demand and its satisfaction.

3. Capacity. Extra potential to produce the transformation needed to satisfy unpredictable demand.

Designing, implementing and controlling the best combination of buffers and variability constitute a primary task for successful management. It is worth noting that properly sized and positioned buffers are not a waste (Pound, Bell and Spearman, 2014).

3.4 Theory of constraints

Theory of constraints (TOC) is a management method which strives to focus on the weakest points in the chain to improve total efficiency. TOC is based on the assumption that each entity has its own detectable bottleneck which impedes a system from achieving higher performance (Goldratt, 1990). Krajewski *et al.* (2016) present seven principles of the theory of constraints. They also present five steps to implement TOC on a practical level.

1. The focus should be on flow balancing, not capacity balancing.
2. Enhancing the performance and output of every resource may not significantly enhance the performance of the entire system.
3. Only the time lost or saved at the bottleneck is significant.
4. Loading the bottleneck at full capacity can be done by keeping inventory in front of the bottleneck. Elsewhere, inventories should be avoided.
5. Any work (materials, customers, documents, etc.) should be released forward into the system only as frequently as the bottlenecks need it.
6. Activating non-bottleneck resources does not increase throughput nor promote better performance on financial measures like utilizing a bottleneck resource which leads to increased throughput.
7. Every capital investment should be viewed from the perspective of its impact on the overall throughput, inventory and operating expenses.

Practical application of the TOC involves implementation of the following steps.

1. Identify the system bottleneck(s). A bottleneck can be internal or external to the firm. Typically, they represent a workstation, a process or a step with the lowest capacity.

2. Exploit the bottleneck(s). Create schedules that maximize the throughput and usage of the bottleneck(s).
3. For all other decisions, refer to step 2. Bottleneck resources should be supported by the non-bottleneck resources and they should not produce more than the bottleneck can handle.
4. Elevate the bottleneck(s). After steps 1 - 3 are done and the bottleneck is still a production constraint, management should consider increasing the capacity of the bottleneck.
5. Do not let inertia set in. Actions presented in steps 3 and 4 will improve the throughput and may alter the distributed loads. As a result, the bottleneck may shift. Then, the practical applications of steps 1 - 4 need to be repeated to identify and manage the new set of constraints.

Bottlenecks can be internal or external to the firm and they typically represent a step, a process or a workstation with the lowest capacity. Throughput time is the time elapsed from the initiation to the finishing of the job. A bottleneck can be detected in two ways. Either the step has the highest total time per units processed or it has the highest average of utilization and total workload. However, variation of the workload can create similar issues such as floating bottlenecks. Thus, the bottleneck varies depending on the load distribution and production mix. This occurs especially if most processes involve multiple operations, and often their capacities are not identical. This type of variability increases the complexity of day-to-day scheduling. In practice, these bottlenecks can be determined by interviewing the workers or supervisors and observing the production line (Krajewski, Malhotra and Ritzman, 2016).

4 CURRENT STATE

The current state of the main processes is presented in this chapter. All data presented in the chapter is from the year 2021 due to low stock slab level. The process illustrations presented in the flow charts were current process descriptions made for the thesis. The thesis's one main aspect is problem identification and process improvement suggestions during a low stock slab level. Accordingly, the most recent year of the low stock slab period was selected as research material. A broad understanding of the order delivery process, production planning, information and material flow in the wholeness of the plate mill's production chain is essential. The basic process of raw iron, steel and slab production and plate mill are illustrated in the following in Figure 3. Specific sub-chapters complement the functions of the core process, in which those functions are sufficiently covered to provide an understanding of the plate mill production chain.

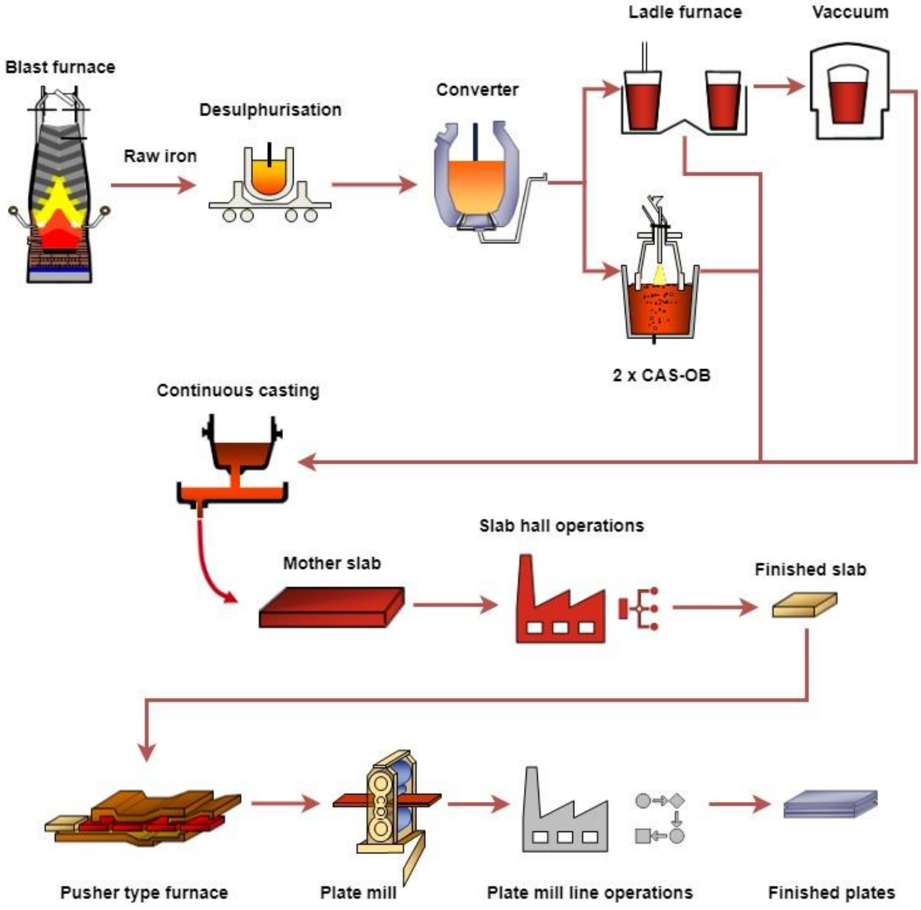


Figure 3 Simplified process graph of raw iron, steel, slab and plate manufacturing (Modified from source: SSAB, 2019).

4.1 Order delivery process

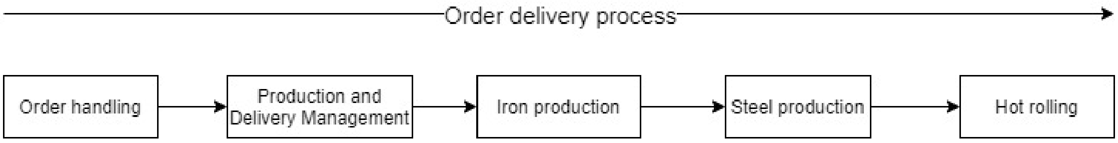


Figure 4 SSAB Raahe order delivery process.

SSAB Raahe's main process is an order delivery process whose target is to produce steel products that fulfil customer needs. The factory's order delivery process is divided into five sub-processes: order handling, PDM, iron production, steel production and hot rolling (Figure 4). The same main process applies to plate and strip production. There are support processes which enable implementation of the main process. Operations are controlled through the EHSQ system. Support processes are maintenance, human resources, laboratories, process development, quality control, safety and environment control (Miettunen, 2019).

SSAB Raahe's main raw materials are iron pellets, steel scrap and cocks. The blast furnace produces the first internal product – raw iron. Blast furnaces are designed to work constantly to ensure raw iron's uniform quality. In steel production the product structure narrows towards converter treatments, after which product structure widens to various steel grades. Raw iron is made into steel by the decarburization process in the converter, where alloying elements are added to match production planning's heat plan. Production planning is organized under the Production and Delivery Management department. Continuous caster casts chemically matched steel into mother slabs which are cut into right dimensions as planned by production planning. Cooled and treated mother slabs are cut into slabs and transported, ready to be charged into the plate mill's pusher type furnace. The second internal product has been made – a finished slab. The hot rolling mill produces high-quality steel plates rolled into target dimensions and treats them by different execution codes and routes. Treated and cut plates are bundled into the dispatch warehouse, ready to be sent to customers via road or ship transportation.

4.2 Information flow before production

In order to study the plate mill's production chain and recognize production flow issues under PDM's influence and also related to low slab level, it is relevant to know the information and material flows in production chain. Order information flow before production is presented in Figure 5. The descriptions of operations of the different organizations have been simplified to adequate level. Hence, the figure shows only the steps that are relevant to the order information flow. SSAB Raahe's production control consists of rough level material controlling and production planning which has more interaction with the production itself (Puominen, 2014).

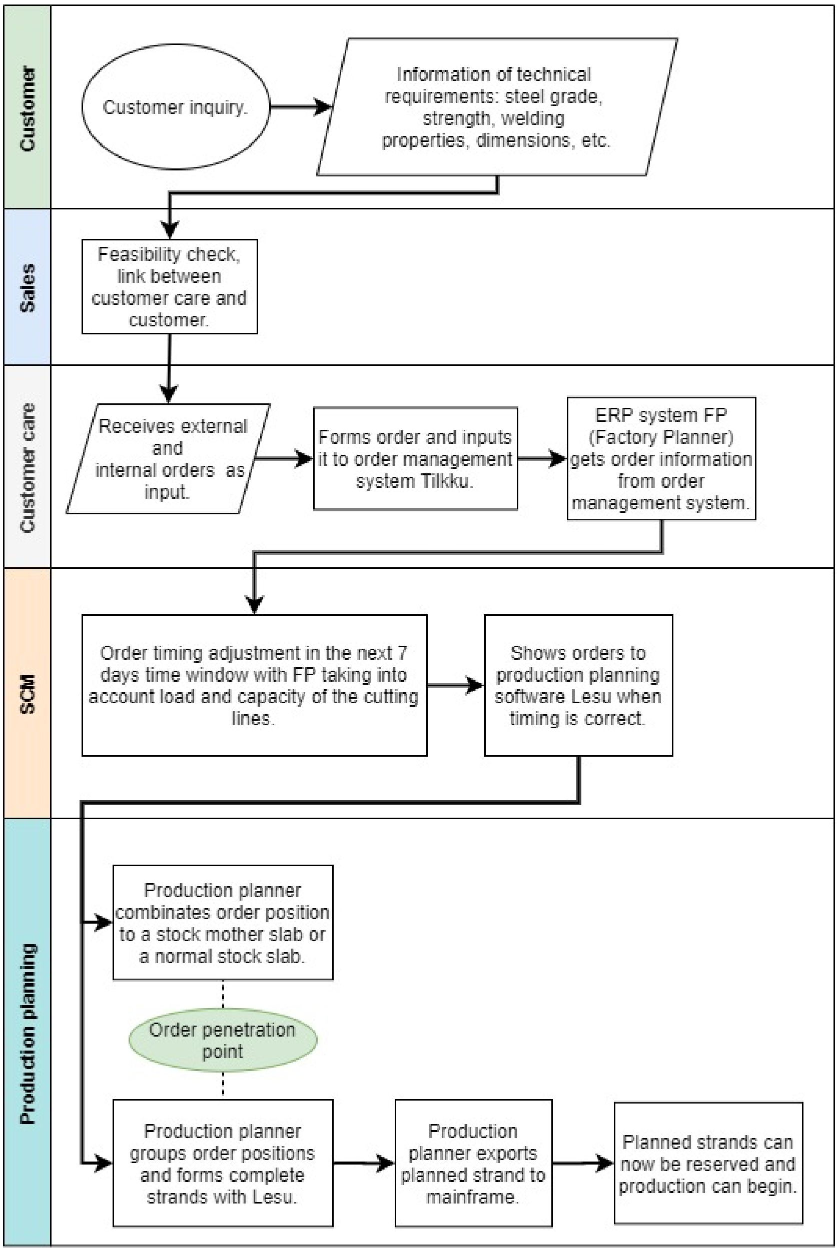


Figure 5 Order of information flow before production.

4.3 Factory planner – load planning

SSAB Raahe's strip and plate mill line's rough material control and load planning are under supply chain management organization and located in Hämeenlinna Finland. The most essential tool for material control and planning is the Factory Planner (FP). By directing order position timing, the FP strives for more optimal and efficient scheduling, including all new orders, parameters, constraints and work in progress. Using these parameters, the program creates a combination, optimum (A.PV), possible start time (PST) and latest possible starting date (LPST) for completion of all orders (Suomela, 2012). The FP is updated every night and during that, new orders are combinated and possible changes in timing are performed. LPST is counted backwards from the delivery date promised to the customer and it takes into account average queue times in different process steps. LPST date does not change during daily scheduling loops and optimization. FP can bring forward or delay order manufacturing dates (A.PV) depending on its optimization. An illustrative example of timing calculation on an overload situation is presented in Figure 6. The current date in the figure is day 0. When the load is delivered by the LPST date, the maximum capacity does not cover the workload. Thus, it is not possible to process delayed and timely orders on that day. When the load is distributed by the PST date, the maximum capacity of the producing unit is utilized but the problem is that production planning sees all order positions as timely or early because the PST or A.PV dates are the ones that are input to production planning software. Load distributed by A.PV is generated by using delay-tolerances which in the presented example is five days so the -6 day load is shown as -1 day. This enables highlighting the actual latest order positions for production planning and utilization of the maximum capacity. Tolerance is used to adjust the amount of load on different lines in the plate mill rolling line and to control production as efficiently as possible through bottlenecks. Another benefit is that production planners can focus better on the worst overdue order positions by showing fewer overdue order positions as timely ones (Harju, 2014; Hallikainen, 2021).

Every day, SCM adjusts the load to plate mill line with a seven-day time window. SCM adjusts the following plate mill line's loads: plate rolling, normalization furnace 1 and 2, mechanical cutting, gas cutting, plasma 7 and 8, tempering, hand packing, ultrasound, inspection and quenching. Needless to say, the SCM timing and load optimization are essential for the material flow of the entirety of the plate mill line's production chain.

However, this work does not take a position on the optimization of the FP or SCM's operations but assumes that the load is timed and distributed optimally because these actions are not under the influence of production planning. In other words, the assumption is that the given production load for production planning is feasible.

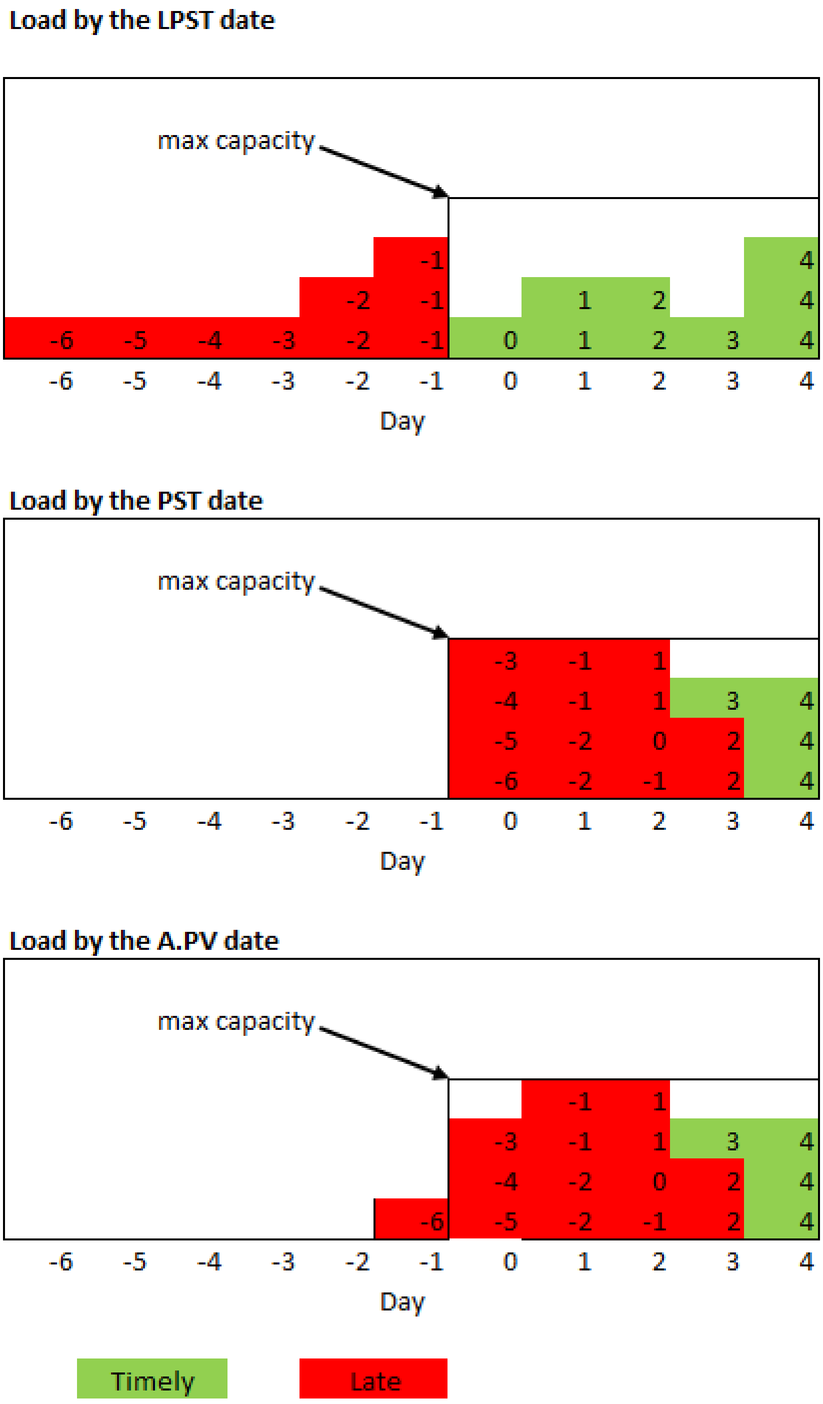


Figure 6 Factory planner timing dates and load example when line is overloaded (Modified from source: Viinanen, 2010).

4.4 Production planning

There are two production planners working around the clock in 12-hour shifts under the production and delivery management (PDM) organization. There is one person in charge of controlling and planning the plate mill's production chain and the other planner works for the strip mill line. The production planner's most important stakeholders are work managers and employees from steel manufacturing (converter, continuous casting), slab halls and the plate mill. In addition to that, many other stakeholders like product planning, laboratory, customer care and order handling are included. The most important operations performed in production planning are order penetration by heat planning or combinating orders to existing slabs and initial or final rolling sequence planning. Combinating is a specific word that is used to describe an action when production planner combines customer order to an existing stock slab. Combinating and other mentioned different functions direct operations through the plate mill's production chain. As shown in Figure 5, production planning gets its order input from SCM's production load and timing software FP. In practice, all the order positions shown to production planning are controlled by SCM. There are two possible routes for order position to transition into production. These are presented in Figure 7. A typical route for order position in production is a production planning heat plan where different, but qualitatively compatible order positions, are gathered to form an ensemble that is called a heat. A set of several heats is called a strand. Heat planning gives production directions to the steel plant and thus it affects production steps after that. Another possible route for order position in production is to be combinated to an existing slab or a mother slab. By combinating orders to existing slabs, order positions are obtained faster for production. In addition, the stock slab level decreases. Production planning is also in charge of planning the initial and final rolling sequences for the plate mill line. Heat planning and sequence planning are discussed in the following chapters.

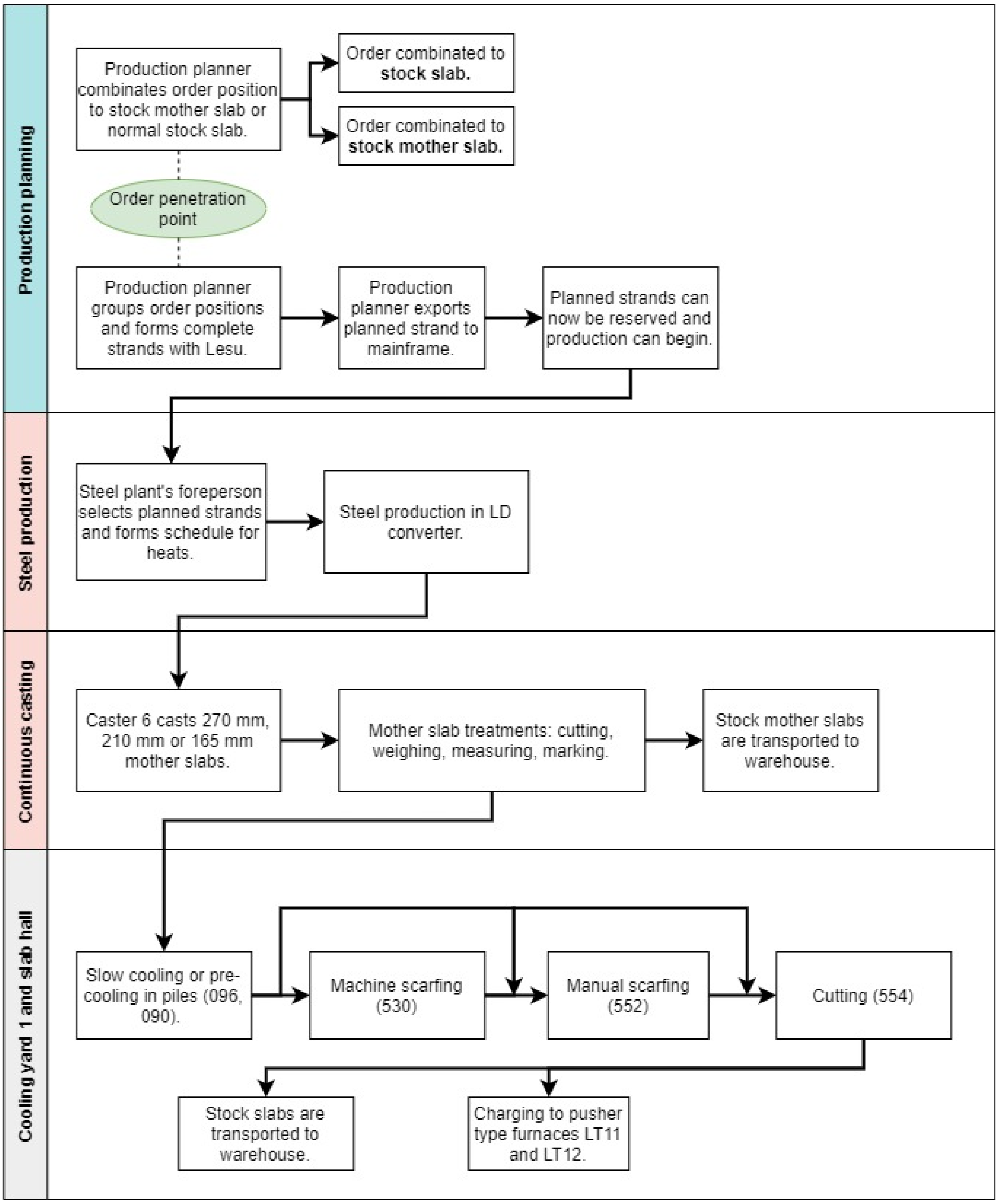


Figure 7 Typical material flow and process steps before plate mill.

4.5 Production flow and management impulses

The plate mill line's production chain can be assessed from many different perspectives. Understanding the principles of information flow and management impulses are essential in order to develop flow improvement suggestions in the production chain. Practical-level production management impulses are presented in Figure 8. The figure starts from the production planning step and shows the main responsibilities and management impulses in production. Roughly speaking, the production planning has four main operations which are heat planning, combination, initial and final sequence planning. These operations are discussed more specifically in other chapters. The figure shows in more detail the different steps in the plate mill production chain before the plate mill and shows how production planning is affecting different operations with its four main actions.

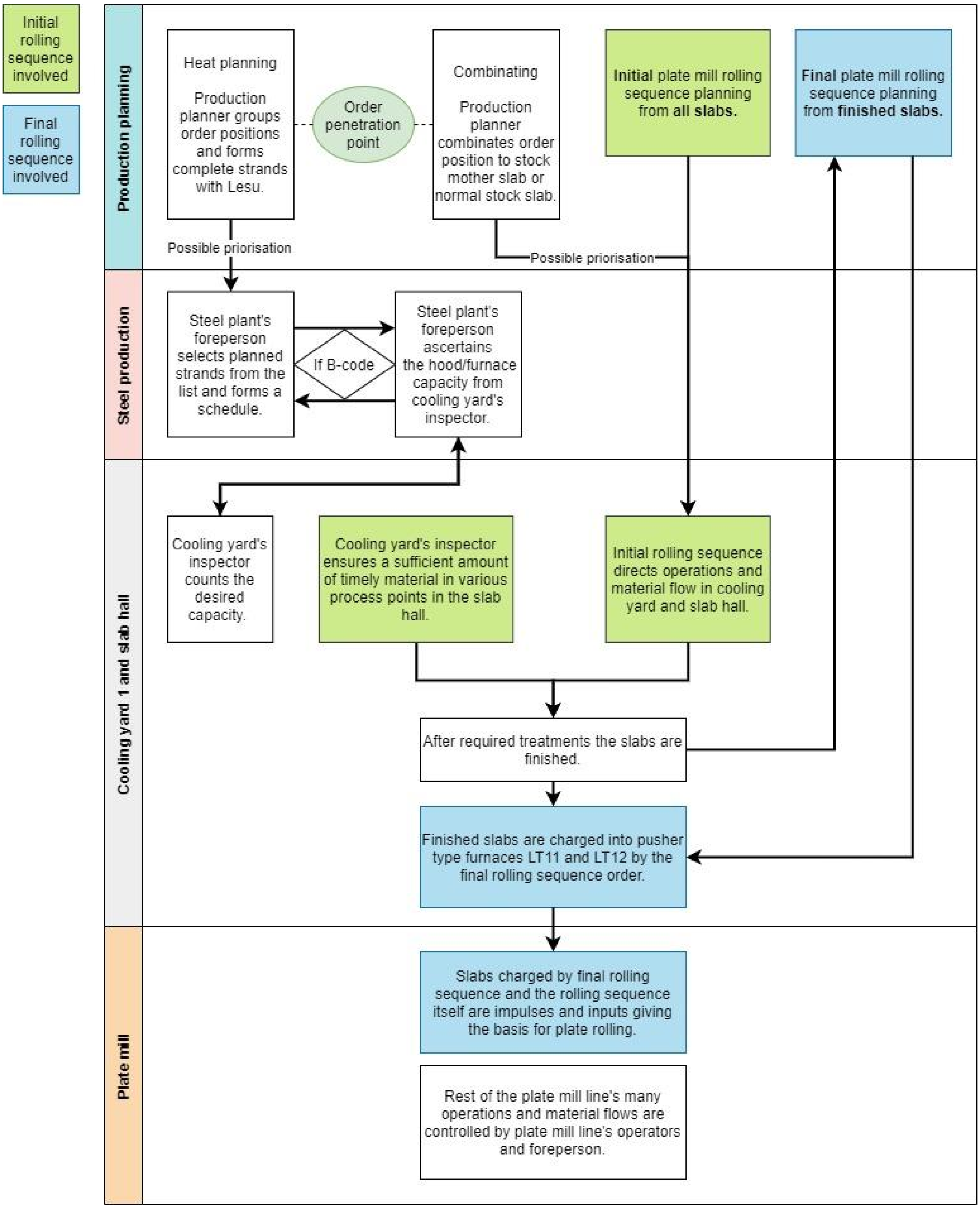


Figure 8 Impulses controlling the plate production chain on a practical level.

Understanding the nature of the process steps before the plate mill is essential for assessing the overall picture. Thus, a need arose for visualization of the material and information flows. A more specific material and information flow chart is presented in Figure 9, which points out production initiation impulses, potentially congested process steps shared with the strip mill line, a few notable circumstances, and thrust and suction. As can be seen, the production has three initiation impulses, two of which are located in the production planning step. The third one is located at the converter step, where the converter foreperson is in charge of the initiation of the production. The first notable circumstance is the exception caused by the converters' production restrictions. These restrictions managing production planning happen frequently, often for various reasons. For example, analysis of the raw iron, condition of each converter, condition of alloying element post-matching units, personnel situation and condition of the continuous caster. These are discussed more in chapter 4.9. The other notable circumstance in the figure is the route of B-coded slabs. Their routings differ in the Naha 1 and Laha 1 in terms of machine- and hand scarfing and cutting, and in general, they require more transportation and treatment, which are discussed further in chapter 4.10.

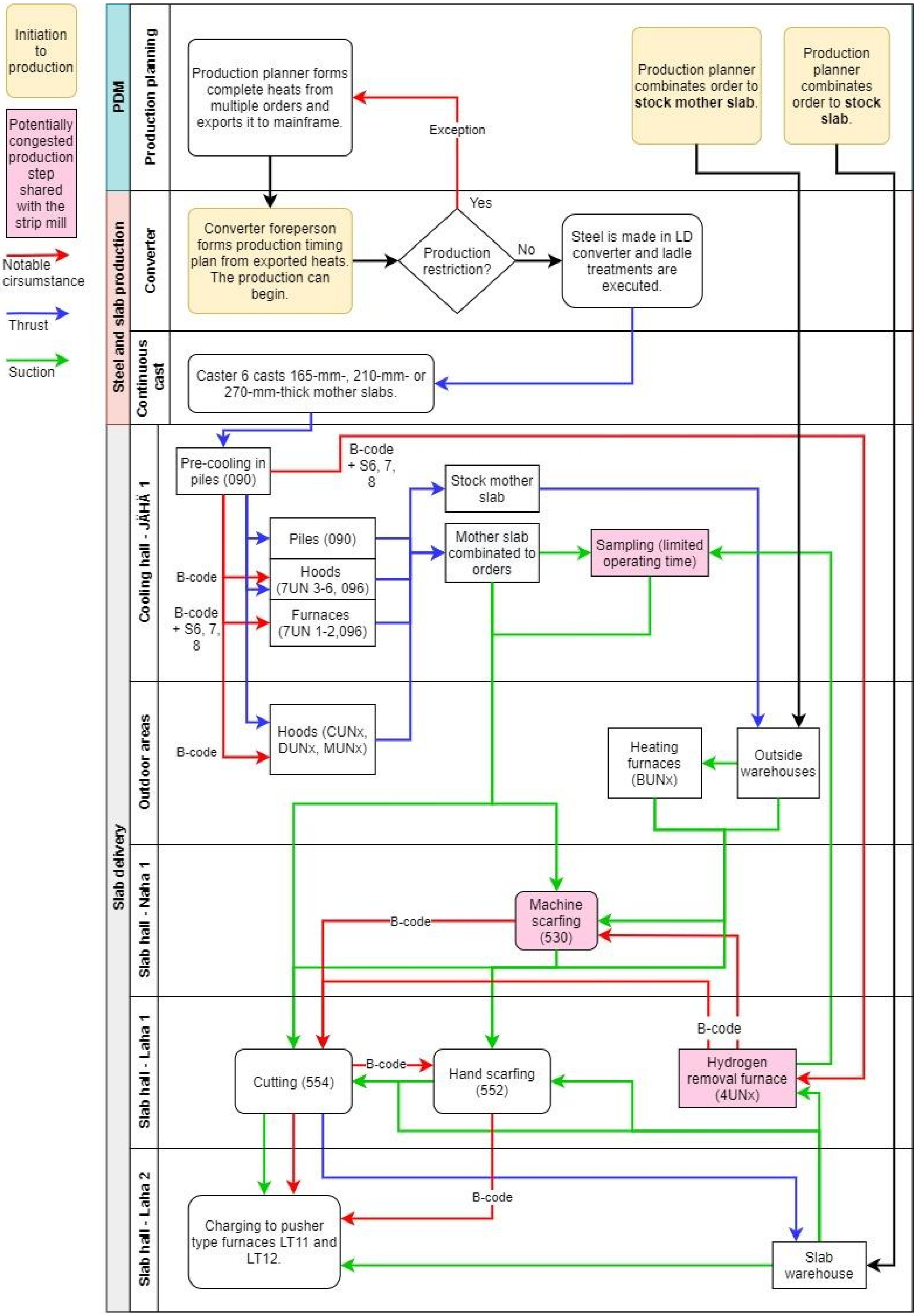


Figure 9 More specific material and information flow chart before plate mill line.

4.6 Heat planning

Production planning is responsible for making complete series of heats by combining order positions and balancing the heat size to match standard sizes by adding stock slabs. Standard heat sizes are 104, 107, 123, 127 t. These sizes depend on the required steel grade and quality and thus, they depend on the converter's production capacity. A heat series, referred to as a strand, can be single, double, triple or a series of four heats. The reason for bundling heats into series is technical implementation of production. The molten steel mixes between different heats inside a single strand. Heats may be, and usually are, slightly different in composition, but qualitatively compatible enough to form a strand.

In 2021, the average heat size was 337 t of steel per strand and there were 5130 different heats which combined total amount of 1682 strands. Average length of a strand is 3.05 ≈ 3 heats. The total amount of cast mother slabs was 21086. The average total count of mother slabs cut from the complete strand's cast strip was 12.5 ≈ 13. The mother slabs are planned to be cast in three thickness options. Continuous caster 6 mould thickness options are 165, 210 or 270 mm. In 2021, 43 % (2200 of 5130) of heats were made in a thickness of 210 mm, 54 % (2765 of 5130) in 270 mm and 3 % (163 of 5130) in 165 mm thickness. The production planner uses the plate planning software Lesu to form the heats and 99 % of the time configures caster 6. Only 75 of 5130 heats are cast through caster 4 or 5, so these are exceptions which are excluded from the study. Casters 4 and 5 are mainly strip plate line casters, but caster 6 is also allocated to the strip plate line's caster when a fitting casting mould is placed. Casts to the strip mill line need to be produced with the casting mould of 210 mm thickness. Consequently, strip and plate mill production planners need to co-operate to allocate caster 6 to strip plate production. The number of strands cast to the strip mill line increases towards the weekend due to fulfilment of the weekly target of plate casting tonnes. This increase is presented in Figure 19 and its significant effects are discussed later in this thesis.

After planning, the strand is exported to the mainframe and the alloying elements are adjusted. Production planners keep approximately 8 strands (20 – 25 heats) in the list, from which the converter foreperson selects planned strands and forms a production schedule. The schedule is supposed to take into account production planning prioritizing or produce strands in chronological order – starting with those that are the longest overdue. The converter's foreperson needs to be aware of several factors before giving the production initiation impulse; these factors are discussed in chapter 4.9. Currently, there are no commonly agreed upper or lower limits for the amounts of strands or heats in the list. Hence the amounts vary between production planning shifts.

In 2021, there were 112 different steel grades cast. Moreover, steel grades are distributed into many different customer grades, making the total number of different quality and measurement combinations very large. The distribution of different steel grades is presented in Figure 10. The figure shows that eight grades covered 53 % of the total in 2021. Hence, there were 104 different steel grades, many of which together make only 1 % of the total amount.

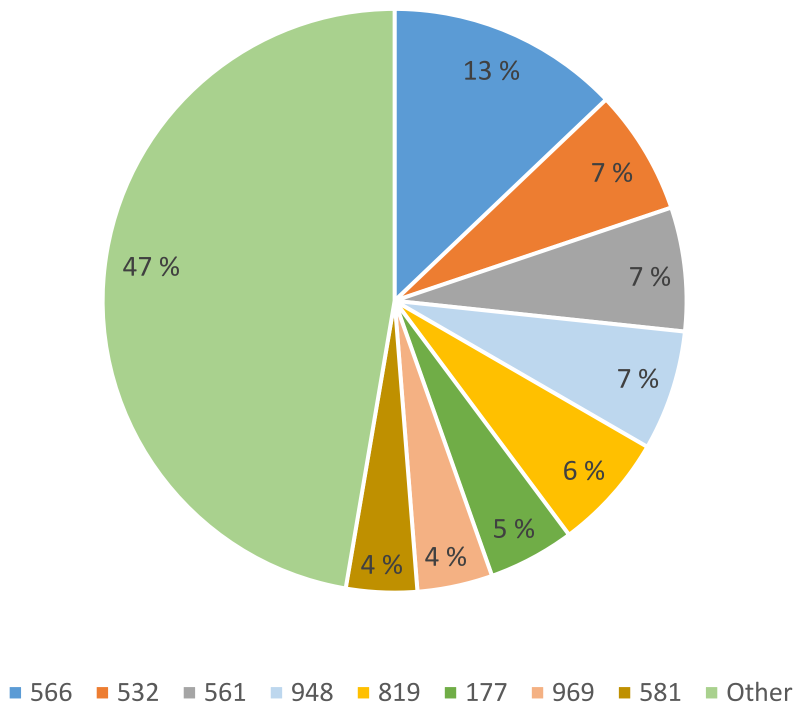


Figure 10 Pie chart of the share of different steel grades cast in 2021.

Dispersion of timeliness of cast heats in 2021 is presented in Figure 7. Standard deviation of timeliness is 9.4 days, mean -1.7 days. It can be seen that a significant portion of cast heats are produced more than 7 days early or 7 days late. Due to the diversity of steel grades and the rarity of some steel grades, the production planning sometimes forms heats from overdue and early order positions to fulfil the standard heat sizes, allowing efficient production. However, this study does not seek to improve timeliness or reduce the dispersion of casting dates. Yet, the dispersion of casting dates is useful for understanding the totality of heat planning.

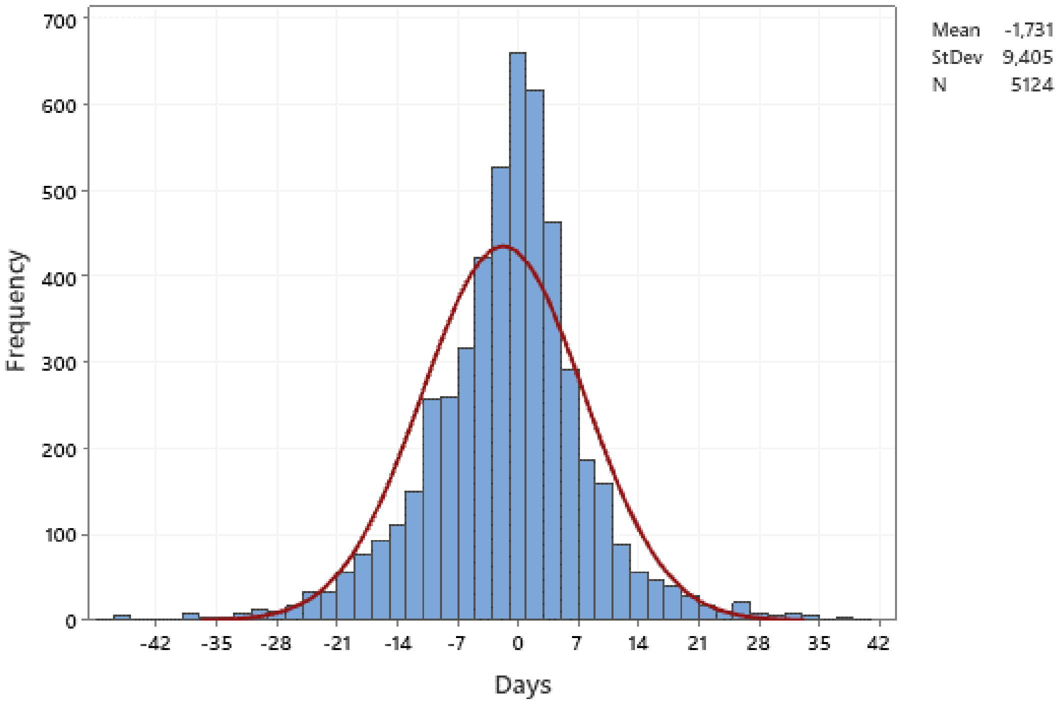


Figure 11 Histogram of timeliness of cast heats for plate mill line in 2021.

4.7 Plate rolling sequence planning

The production planner is responsible for making a rolling sequence with the Jasu software. Rolling sequence controls the operations in the plate rolling mill but also in the slab halls. Slab hall operations are discussed in chapter 4.5.2. The sequence planning's core function is to form the most favourable plate rolling sequence from currently finished and unfinished slabs taking into account production restrictions and sequence forming rules. Automatic planning has been tested but manual has proven to be more effective. One rolling sequence is planned to be 600 slabs long and after that one of two work rolls is replaced, making the total amount of rolled slabs 1200 per work roll.

There are several rules to be noted when forming the rolling sequence with Lesu. The most important of which is to divide the slabs into two pusher type furnaces: LT11 and LT12 (LT 11 with a lower operating temperature). The initial sequence is continuously adapted as the production planner places recently produced and combinated slabs in the list. The initial sequence list controls the operations in the slab halls. Operating on a good stock slab level there are approximately 800 – 1200 slabs on the initial list. A good functional level of finished slabs is considered over about 400. The level is considered bad when under 300 finished slabs. When the slab treatments in slab halls are finished and the slab is transported into the furnace charging area, production planning can either make changes to the initial sequence or release it on to the final sequence list as it is. A notable circumstance is that production planning can only release finished slabs. This final sequence list controls the work in the slab hall Laha 2 furnace charging area and in the plate mill.

Working with low stock slab level decreases production planning's options to form initial and final sequences as the number of finished slabs decreases. Generally, at low stock slab level, production planning tries to find compromises and sometimes unfavourable decisions need be made. There are a few ways in which production planning can cope with these situations. Sometimes limiting the plate mill's production is necessary by ceasing operation of the other pusher type furnace because available slabs are completely used. Usually, the production is paused in LT12 because LT11 is more efficient. Sometimes this leads to an increase in temperature in LT11 to the LT12 operating temperature because some steel grades planned for production in LT11 have an option for higher heating temperature. Consequently, some slabs from the LT12 initial list can be transferred to LT11. Transferring the slabs from LT12 to LT11 causes extra logistics in the charging area because the slab hall crane operators have already sorted the slabs in the charging area. There can be situations when the slabs run out and operation of both pusher furnaces must be ceased. Therefore, ceasing slab mill operation is necessary, although much is done to avoid this situation. The general operating model is to keep the plate mill running. At the moment, production planning finds it challenging to predict whether the finished slabs will run out or not. In some cases, production planning is able to form the rolling sequence from a rather low number of finished slabs (100 - 200 pcs.). On the contrary, in some cases forming a rolling sequence and releasing it to production is not possible, even with a higher number of finished slabs due to the plate rolling sequence forming restrictions.

4.8 Quality of the rolling sequence

The rolling sequence is an essential production-driving impulse. Thus, it gives the basis for the operation of the entire plate rolling mill line. Therefore, the content and the quality of the sequence need to be discussed. The content of the initial rolling sequence is a natural consequence of the previous days' casting production and combinated slabs combined minus the previous days' consumption. Consequently, the composition of the initial rolling sequence has been found to vary strongly due to the diversity of order backlog and the current production situation. That diversity is reflected in the final rolling sequence as the buffer of finished slabs decreases. To illustrate the situation, Figure 12, Figure 13 and Figure 14 show examples made by the author. The strand production order is presented in Figure 12. The normal functional level of slabs in total in the initial rolling sequence is 800 - 1200 slabs. In 2021, average slab weight (6.11 tonnes) it makes 4888 - 7332 tonnes of steel or 15 - 22 cast strands. The average strand size being 337 tonnes. In 2021, the average strand production per day was 4.6 strands so casting production of 800 to 1200 slabs takes 3.3 to 4.8 days. As can be seen, there are strong variations between strand sizes in tonnes because strands are formed from one to four heats.

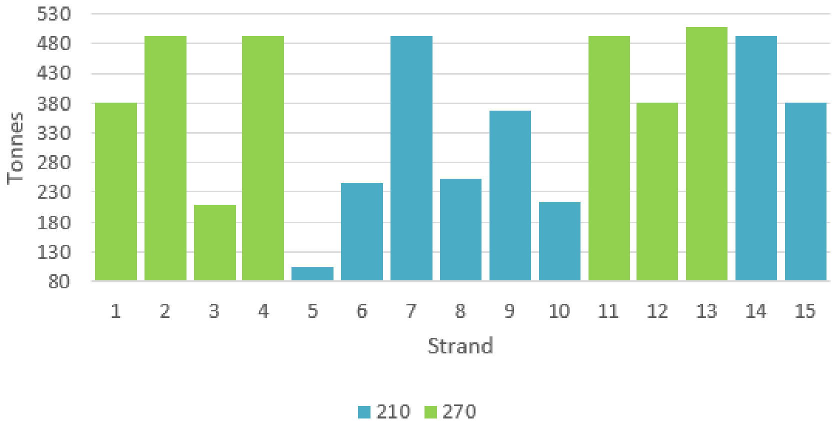


Figure 12 Example of the production order of 15 strands.

An example of the content of each strand is presented in Figure 13. The figure shows an example of the proportion of each cutting option with reference to the strands shown in the previous figure. Naturally, every strand consists of a portion of stock slabs which afterwards are combinated to a customer order. These stock slabs are not relevant to this example. In general, thicker slabs (270 mm) are more likely to be rolled into thicker plates. Thicker plates are usually routed to be gas-cut. On the contrary, thinner plates rolled from thinner (210 mm) slabs are more likely to be mechanical-cut. This rough division has proven to be a general rule among production planners. For instance, if the plate mill's mechanical load grows too high, production planners may use this rule and prioritize 270-mm-thick strands.

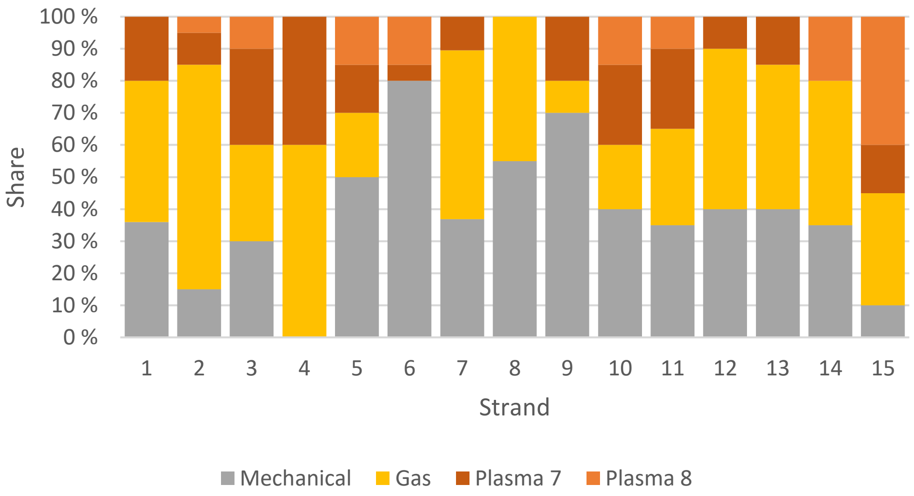


Figure 13 Example of the content of the produced strands. Customer slabs only.

When the supply of finished slabs does not meet the consumption, the number of finished slabs decreases. Thus, it shrinks the options to form a rolling sequence. The cutting capacities of the plate mill line are presented in Figure 14. It shows that nearly half of the load in tonnes is planned to be mechanically cut, nearly a third to be gas-cut and the rest plasma-cut. As the buffer of finished slabs decreases for some reason, the cutting variations of the cast strands reflect more easily on the final rolling sequence because production planning has fewer options to balance the situation and form a sequence that best serves the production situation in terms of cutting capacity and thus production flow. In addition, the strong variation of casting tonnes may emphasize already unfavourably weighted distribution.

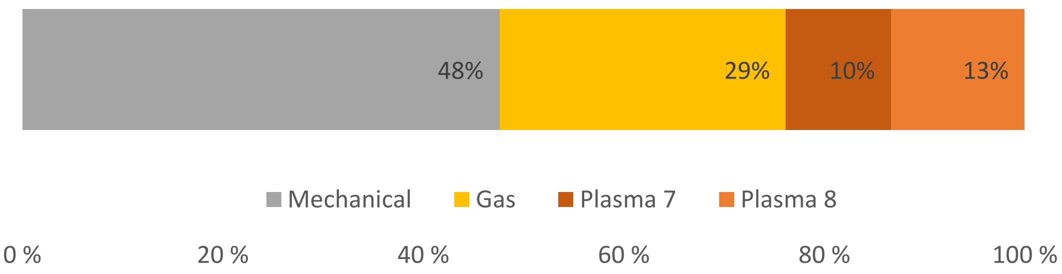


Figure 14 Cutting capacity proportions of plate mill line by tonnes.

Realized distribution of cutting options by casting moulds is presented in Figure 15. It shows that the majority of 210 mm slabs are mechanical-cut in the plate mill and 57 % of the 270 mm slabs are gas-cut.

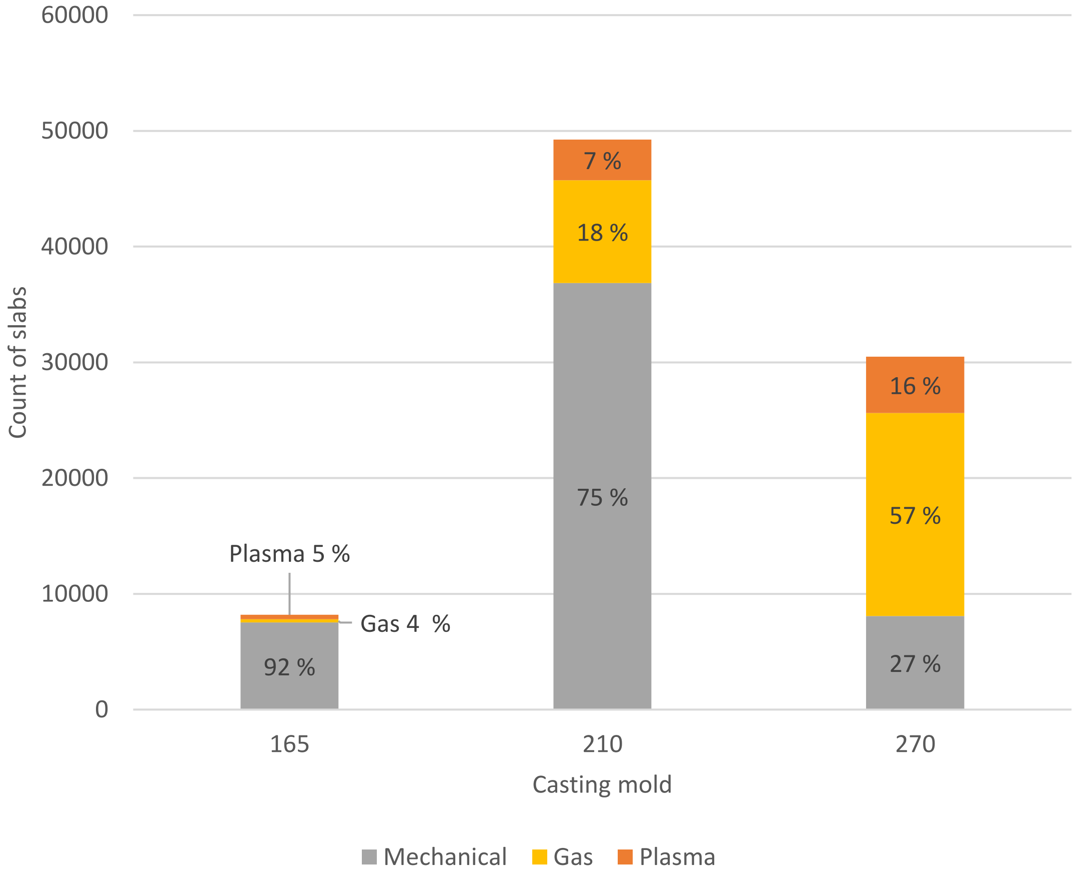


Figure 15 Realized cutting routes in plate mill by casting moulds in 2021.

Slab weight variation and the cutting route shares for 210 mm and 270 mm casting moulds are presented in Figure 16 and Figure 17. It can be seen from Figure 16 that the count of slabs decreases as the slab weight increases. The average weight of a 210 mm slab in 2021 was 4.8 tonnes, whereas the 270-mm-thick slabs' average weight was 9.3 tonnes. The change of the share of some cutting routes occur when slab weight changes. For example, the proportion of 210 mm gas-cut slabs increases as the slab weight increases or the 270 mm mechanical-cut share is larger with smaller slab weights. Figure 18 illustrates the share of different rolling thicknesses since the other figures deal with slab weight. The figure shows that the majority of 210 mm slabs are rolled to 5 - 25 mm thickness and they are mechanical-cut. Another significant proportion of mechanical-cut slabs are 270 mm with a rolling thickness of 15 - 25 mm. Due to the variation of cutting route shares of each casting mould combined with variation in slab weight, the distortion of the rolling sequence seems relatively possible.

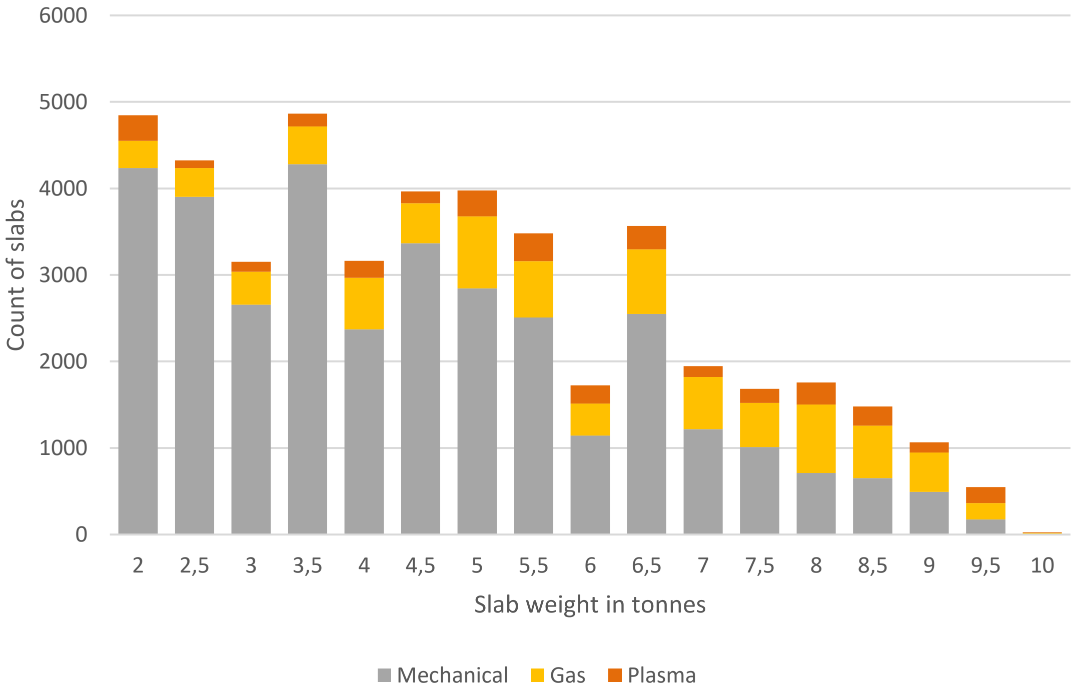


Figure 16 Proportion of cutting routes for 210-mm-thick slabs by slab weight.

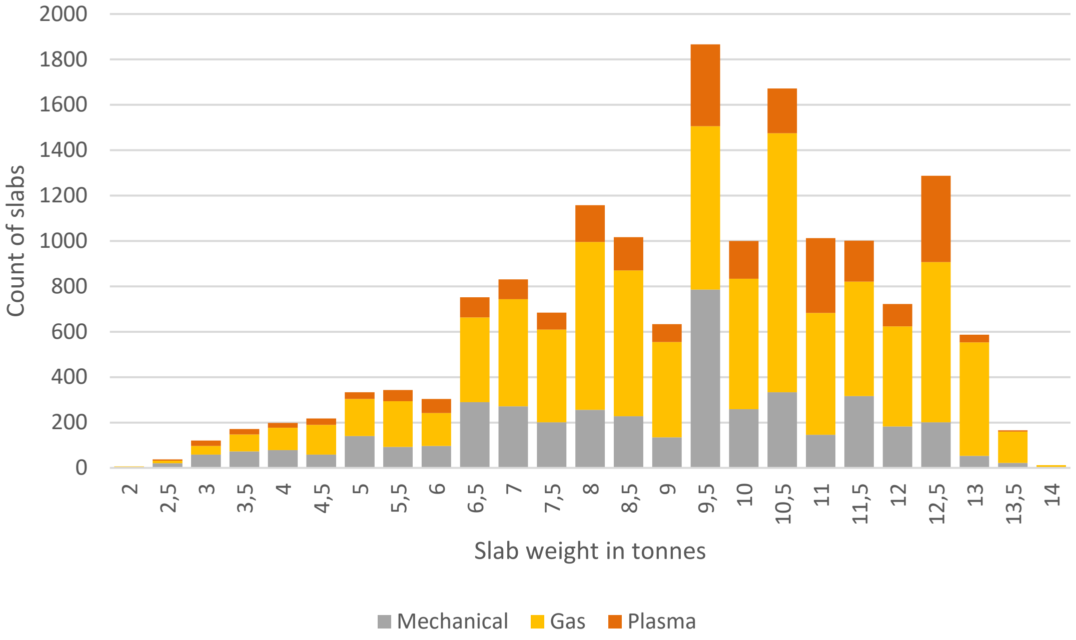


Figure 17 Proportion of cutting routes for 270-mm-thick slabs by slab weight.

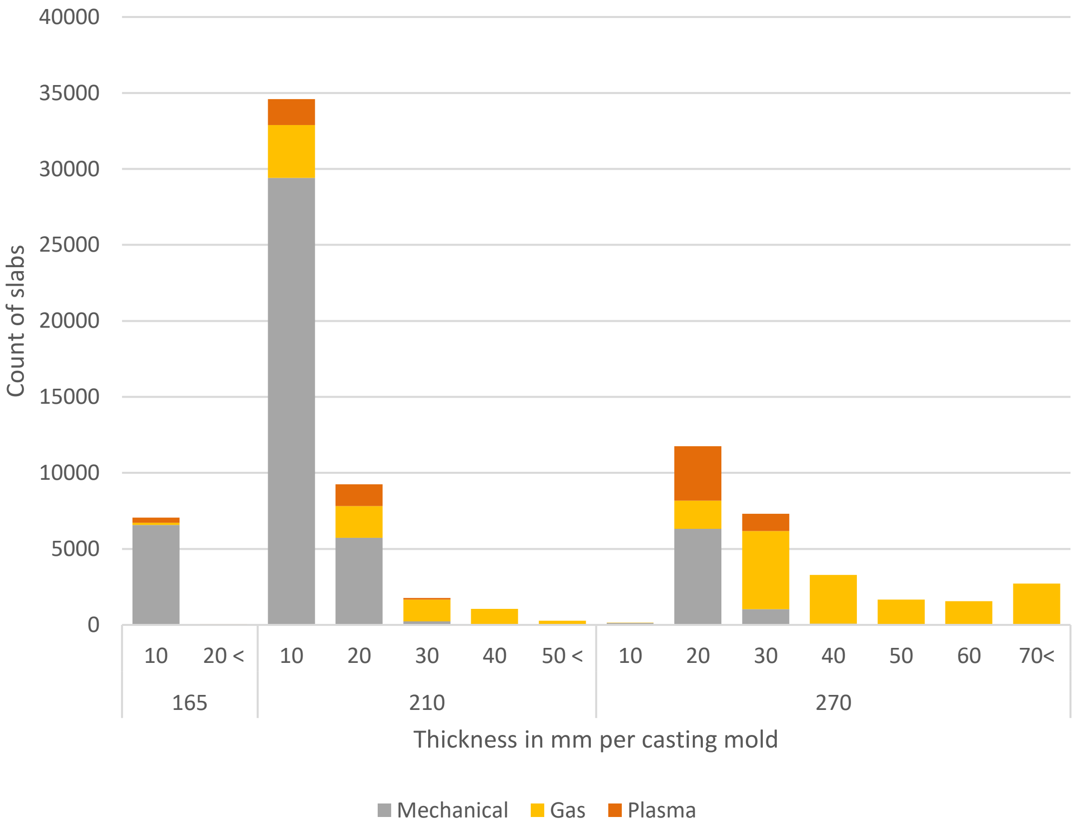


Figure 18 Proportion of cutting routes for each casting mould by plate thickness.

4.9 Converters

A steel plant has basically two running modes: two and three converter models. Within the past 10 years, both running modes have been used depending on the market situation. At the time of high demand, the running mode is generally on three converters. So, the basic running model is either two or three converters depending on the sum of several variables. There is, for instance, some maintenance that can momentarily set production on two converters, but that does not necessarily mean lower production. Running on three converters gives more freedom to the converter foreperson for forming the timing model and following production planners' prioritization. On a two converter model, it is essential to optimize the running time of both converters to ensure continuous production. A two converter running model occasionally sets requirements for production planning to plan strands with certain treatments or to optimize strand length to be either longer or shorter. Therefore, not all production goes under production planning plans and direction. These exceptions and their place in the plate mill's production chain are shown in Figure 9. The figure also highlights that the impulse to initiate steel production is located at the steel plant and not at production planning, in contrast with slab combination. Based on several interviews, converters' work management and production manager were of the opinion that production would work best if the production was continuous and steady. This relatively common statement refers to the production being somehow unbalanced (Converter shift supervisors, 2021; Pärkkä, 2021).

Converter work management selects several strands the production planner has made and defines process routes for these, and finally forms a timing model. The timing model is the basis of operations in a steel plant. Taking into account several factors is essential when making decisions and planning the timing model. For instance, influencing factors are analysis of the raw iron, condition of each converter, condition of alloying element post-matching units, personnel situation and condition of the continuous caster. Operating in a normal production situation, the very basis of a steel plant's operation is to keep the usage of raw iron at approximately the same level as blast furnace production and adjust all converters' production to load bottlenecks like desulphurization and vacuum degasser units. A steel plant gets its weekly production targets from PDM's operation planner. The operation planner calculates weekly targets by planned loads and order positions, taking into account the converter's weekly production restrictions, like maintenance (Converter shift supervisors, 2021).

4.9.1 Steel plant's production control

Exported strands formed by heat planning are the main impulse from production planning that is given to a steel plant in a normal production situation. The strands can be prioritized to highlight their importance. Production planning's prioritization practices have some variation between shifts and in different production situations. The most common reasons to prioritize are directing production by date (latest casting day first) or prioritizing strands which have order positions with especially high importance. Production planning typically does not take into account order position routes in the slab hall or in the plate mill line when prioritizing strands (Production planners, 2021).

The B-coded strands require extra attention from steel plant work management. Before taking strands into production that include a B-code, the converter's foreperson ascertains the hood/furnace capacity from the cooling hall's inspector, whose main responsibility is to manage hood loading and unloading. Consequently, the B-code castings require more management at the very beginning in the production chain, and care is required to allow smooth flow through the slab hall. However, sometimes extra processing and logistics of B-coded slabs are encountered in the slab halls. Strands without the B-code do not require any more than cooling space in the cooling hall, hence they can be cast more freely (Inspectors, 2021).

4.9.2 Caster 6's cast strands

Normally, casting capacity allocated to the plate mill line is around 9500 - 12000 tonnes, whereas plate mill rolling capacity is 11000 or 11600 tonnes depending on the maintenance cycle. Caster 6 is also allocated to the strip mill line depending on the production situation. The amount of cast strands per weekday is presented in Figure 19. In brief, the figure shows that plate mill casting volumes decrease as the week progresses, whereas strip mill casting quantities increase.

The figure shows that the highest amount of plate strands are cast on Tuesdays (5.9 pcs) and the lowest amount on Sundays (2.6 pcs). The average number of cast plate strands is 4.6. The most strip casts from caster 6 are made on Sundays (3.7 pcs) and the least on Wednesdays (0.8 pcs). At the moment there are no daily nor weekly goals for the number of cast strands. A steel plant only has a weekly target in tonnes. Production planning is currently not striving to manage the strand casting amounts or equalize production for the days of the week.

Based on the interviews conducted in the slab hall, strands with the B-code cause a large share of the challenges. Challenges in adequacy of a contractor's resources and hot cutting capacity occur due to the mother slab's simultaneous complete from slow cooling. These issues are discussed in chapter 4.10. Figure 20 shows that total casting volumes vary between weekdays, but the share of B-coded strands seems to stay rather constant. This is complemented by Table 1, which shows that the share of B-coded strands varies between 25 - 35 %.

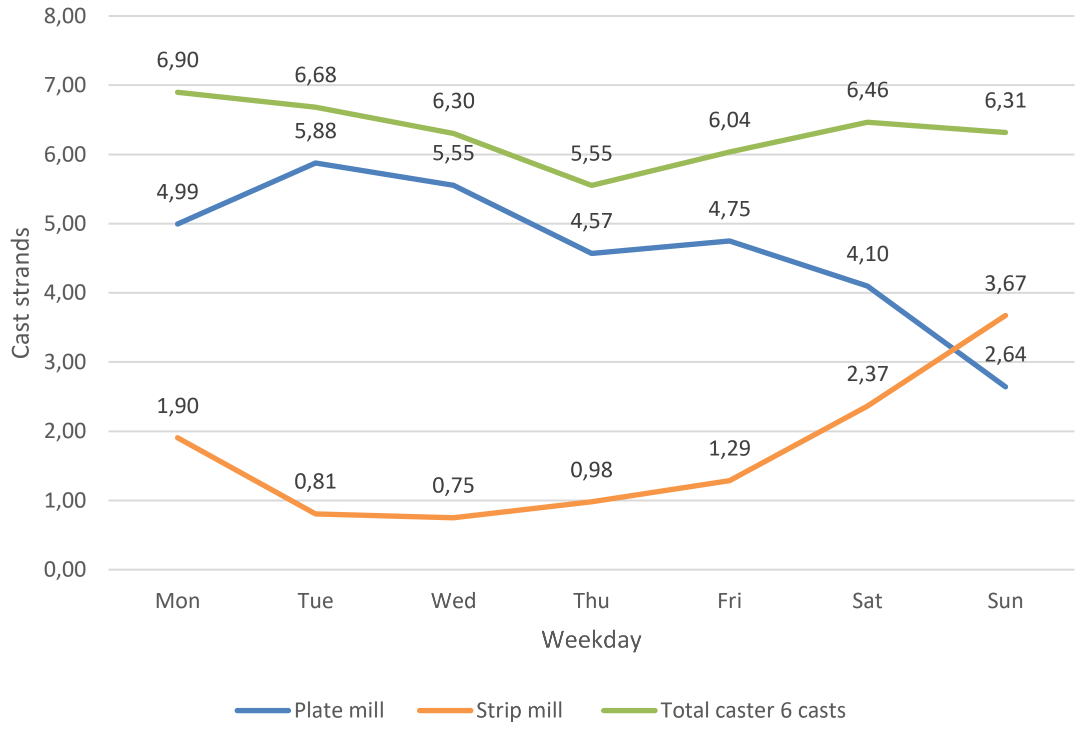


Figure 19 Caster 6 cast strands.

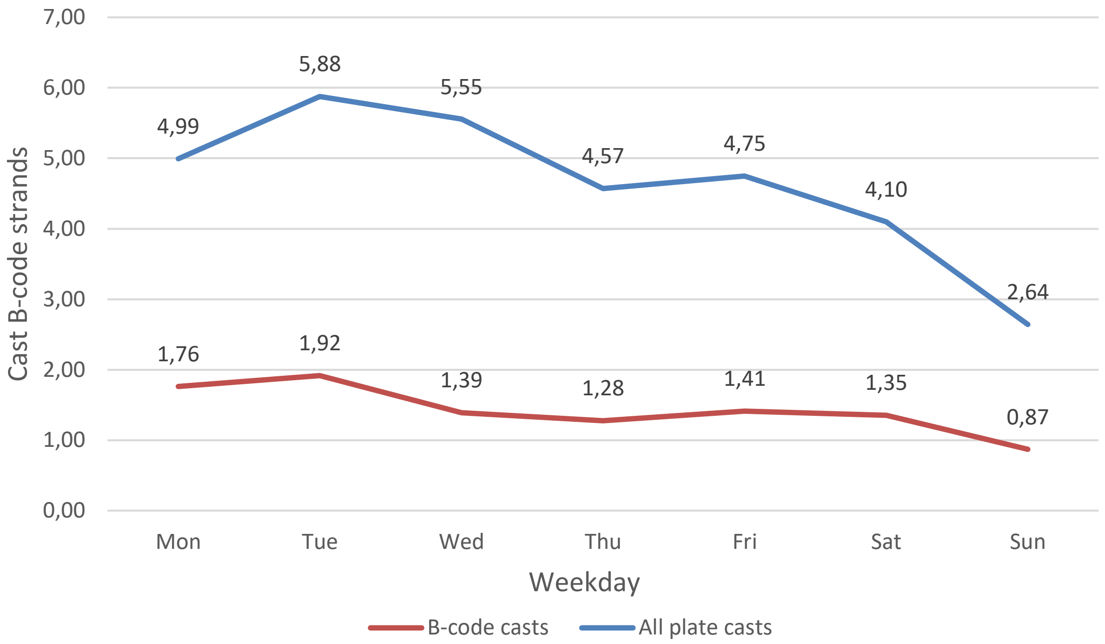


Figure 20 The proportion of B-code strands in the total plate cast strands

Weekday	Cast plate strands	B-code strands	B-code percentage
Mon	4.99	1.76	35%
Tue	5.88	1.92	33%
Wed	5.55	1.39	25%
Thu	4.57	1.28	28%
Fri	4.75	1.41	30%
Sat	4.10	1.35	33%
Sun	2.64	0.87	33%

Table 1. B-code strands share of total cast strands per week.

Variation between castings per casting moulds can be seen in Figure 21, which shows the number of strands for each casting mould per weekday. Castings with the 210 mm mould are rather constant, though the number decreases over the weekend. A noticeable difference can be seen from the 270 mm line graph. The highest number of strands is cast on Tuesdays and Wednesdays and Figure 19 compliments this by pointing out that most of them consist of 270-mm-thick castings. The 165-mm-thick casts are not included in Figure 21 due to their marginal share.

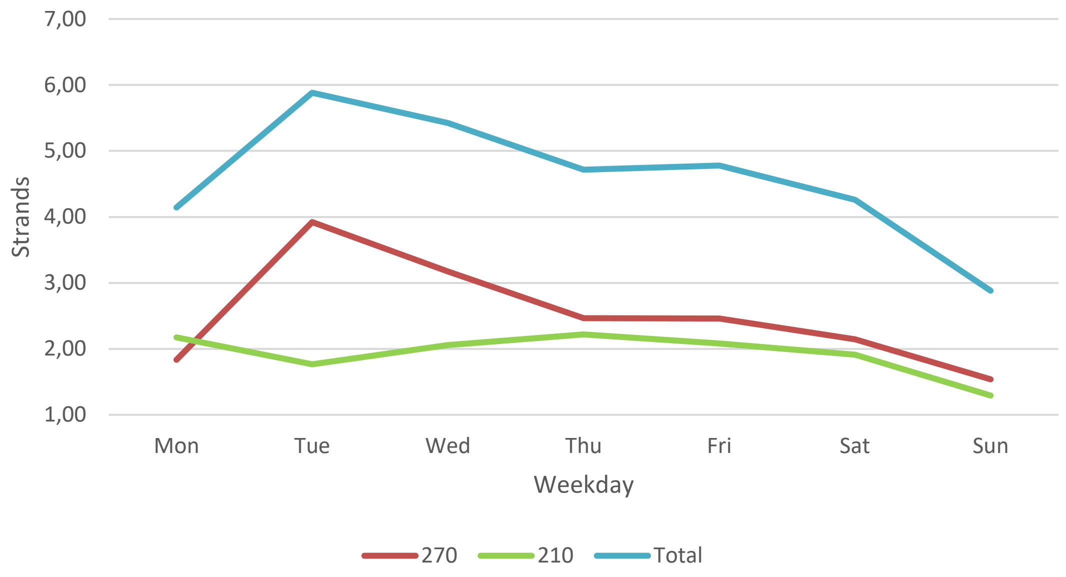


Figure 21 Caster 6 number of cast strands for plate mill line with different casting moulds per weekday.

The impulse for the casting mould replacement generally comes from production planning, but sometimes the impulse may come from the production. The reasons beyond the control of production planning can be, for instance, insufficient hood capacity or a mechanical fault at the steel plant. The casting mould change is an efficient procedure as it only takes about 15 - 25 minutes. This time is not considered to significantly disrupt production. Currently, production planning infers the need for mould replacement based on current order positions and their urgency. Thus, the mould is changed as needed. The number of mould changes per week is presented in Figure 22 and it points out that there is a strong variation between mould changes in different weeks. Figure 23 and Figure 24 show the histograms of two of the main casting moulds and how long the moulds have been in place. The figures show that the 210-mm-thick mould is set more frequently for a longer time than the 270-mm-thick mould. There are deviations in Figure 23 at 3 – 3.5 and 4 – 4.5 days, indicating that the mould is often in place for much longer than usual, and thus, the distribution does not decrease evenly. No similar deviation can be seen in Figure 24, which shows that longer set times are becoming less frequent. The graphs show that the typical set time for a 210 mm mould is 1.5 – 2 days, whereas for a 270 mm thick mould it is 1 – 1.5 days. The longer time for a 210 mm mould is not explained by the casting speed since there is no difference in casting durations between the moulds. In addition, 43 % of casts in 2021 were made with 210 mm thickness and 54 % with 270 mm. The longer continuous usage period for 210 mm mould is probably explained by the partial allocation of caster 6 to the needs of the strip mill line.

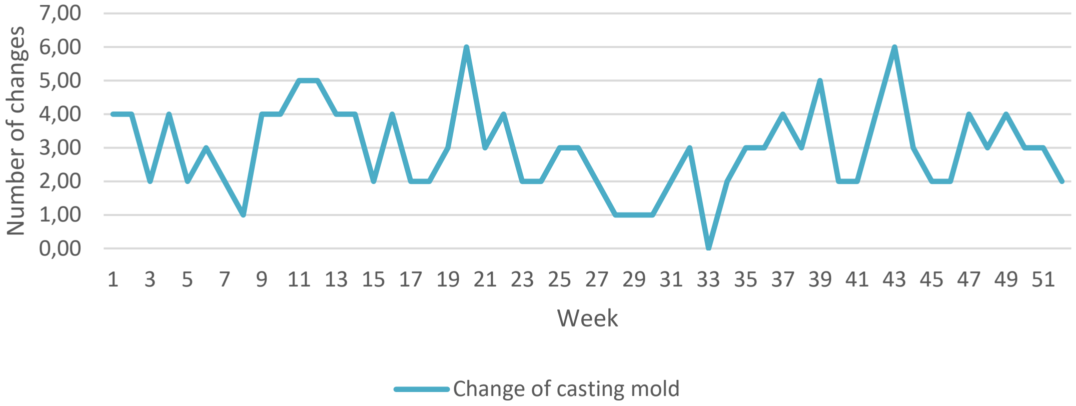


Figure 22 Number of mould changes per week in 2021.

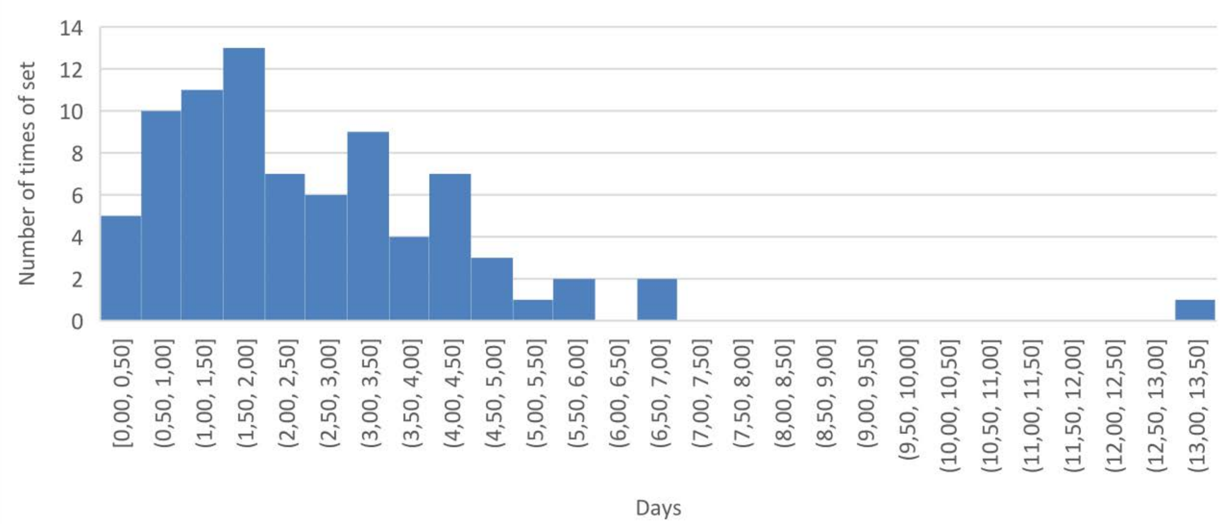


Figure 23 Histogram of 210-mm-thick casting mould.

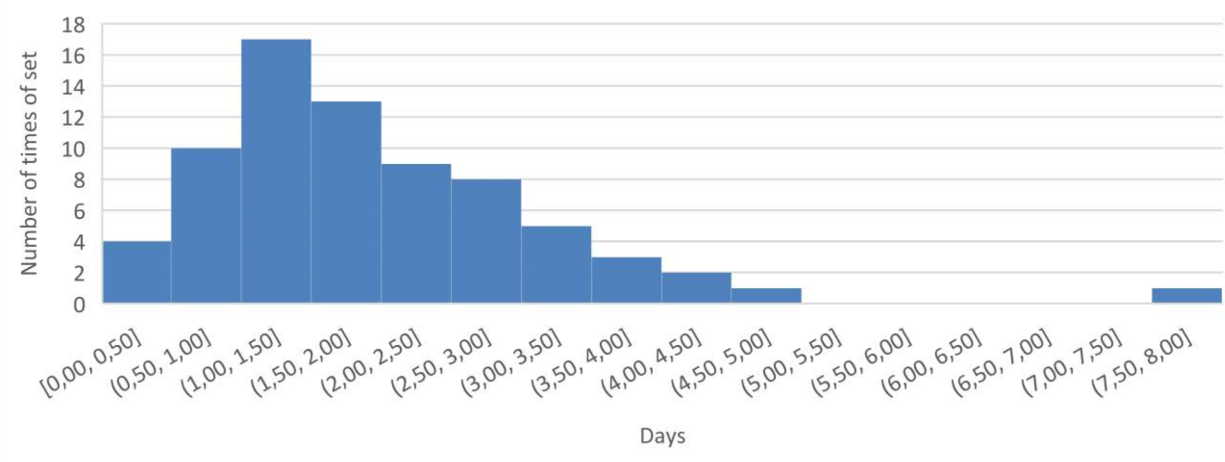


Figure 24 Histogram of 270-mm-thick casting mould.

4.10 Slab hall and cooling yards

This chapter discusses two different kinds of halls because of their logical necessary co-operation. The function of slab halls and cooling yards is to operate as a processing point and intermediate storage between the steel plant and mill lines. The aims of the halls and yards are to take care of an up-to-date storage system and to deliver slabs of correct weight, length and checks to meet treatment requirements to the plate and strip mill in a timely manner. A slab hall contains numerous process routes and operations can be performed in multiple orders. On the contrary, cooling hall process routes are rather simple. The operations in the cooling yard and slab halls are directed by the initial rolling sequence made by production planning. Operations (charging) in the Laha 2 area are controlled by the final rolling sequence.

4.10.1 Slab hall production prioritizing

When the production planner combinates order positions to an existing mother slab or slabs, the slabs are treated faster, and thus, the rolling can be done quicker. This manual combination is done for many reasons. For example, some plates have been rejected in production or the order position is manufactured only partially, or the order positions are urgent. Production planning can prioritize slabs that are currently unfinished work in process (WIP) in the slab hall's operation area. The prioritizing can be done in three ways: by placing the rush-orders on the top of initial rolling sequence lists, which generates the smallest working order number, or by delivering the high-urgency information by calling or writing it on the diary. Based on the interviews, there are some prioritized slab-related information flow challenges between production and production planning. These opinions vary between shifts. Some slab hall employees would prefer the way of prioritization, which gives the slabs the smallest working order number. Every slab gets that working order number, called the page number. The numbering is consecutive, with the slab of the smallest number being the most urgent one, etc. That number order in the slab hall production is the main managing impulse. From the point of view of the employees, delivering high-urgency information by calling or writing it in a common diary might lead to an interruption of data transfer between employees, and thus, between different process steps. From the point of view of production planning, it is laborious to pick every urgent slab on the initial rolling sequence and place them on top of the lists in places where they cannot be placed within the design constraints of the rolling sequence. However, it can be stated that there is no commonly accepted way for production planning to prioritize slabs in the slab hall, and occasionally information flow interruptions arise (Production planners, 2021).

4.10.2 S and B-codes

Certain steel qualities require slow cooling in heat insulating hoods or long treatment in electrical furnaces to achieve desired metallurgical properties. These metallurgical properties are frequently related to hydrogen diffusion and cracking sensitivity. Execution codes specifying hydrogen removal treatments and slow cooling are S and B codes.

The B-code is a temperature-dependent executive code that specifies that the slabs need to be scarfed and cut at the specified temperature. The S-code is a hydrogen content-dependent execution code that directs slabs to furnaces depending on the measured hydrogen content or by default. Typically, plate slabs contain code B5 and additionally some S code between 1 – 8. Code S6, S7 or S8 with or without the B-code directs material to furnaces where treatments take 100 – 384 h depending on the S-code. Approximately 31 % of all slabs in 2021 were slabs with a B-code. The share of the B-code is expected to increase due to the growing share of the automotive industry in SSAB’s customer portfolio (Tarkka, 2021).

Cast mother slabs from caster 6 are transported to cooling yard 1, whereas mother slabs from caster 4 and 5 are cast to cooling yard 2. As presented earlier, mother slabs for the plate mill are cast with caster 6 and thus transported into cooling yard 1. The logistics of the cooling yard area and material flow from the cooling yard is controlled by a cooling yard inspector. The inspector’s main functions are material flow control by directing mother slabs. Mother slabs can be directed to be loaded into cooling hoods or furnaces or unloaded to ensure enough timely material in different process steps in the slab halls. The importance of inspectors in material flow coordination is emphasized because the current controlling system does not reflect the relative order of importance of the slabs. The only managing impulse is the initial rolling sequence. Effective communication is necessary between mainly crane and slab hall operators, contractor, steel plant’s foreperson and production planning. SSAB has outsourced the operations of reach stacker and yard truck to a contractor (Härkönen, 2021; Kärkkäinen, 2021; Vasankari, 2021).

Due to critical restrictions on treatment temperatures of these slabs, additional processing occurs in the form of re-heating and extra logistics. Production planning can ease the extra logistics by combining as many order positions as possible to these slabs. This practice is at least partially in place (Production planners, 2021).

4.10.3 Process flow and routes

Essential process routes and material flow are presented in Figure 9. The first process step in cooling yard 1 is to pile the mother slabs into pre-cooling piles. After that, the execution codes S and B determine the required process routes. As presented in the figure, the following process steps for these execution codes are either cooling hoods or hydrogen removal furnaces. The S-code determines whether the mother slab routing leads to a hydrogen removal furnace. After the required processing, the mother slabs without an order position combination are directed to outside warehouse areas. The rest continue to sampling or go straight into slab halls. Three different processes can be applied there: machine scarfing, hand scarfing or cutting. Because of the possibility of different types of defects (cracks, holes, etc.), the strand’s first heat’s first mother slab is directed to Naha 1 machine scarfing. The rest can be directed to machine scarfing (depending on defects or order position requirements), hand scarfing, or straight to cutting. Mother slabs can include both stock slabs or slabs with an order position. After cutting, the stock slabs are transported into the Laha 2 slab warehouse, whereas the rest continue to the Laha 2 rally area where crane operators charge them into pusher type furnaces according to the production planners’ final rolling sequence.

When slow cooling in hoods or hydrogen removal furnace has been finished, the mother slabs with B-code have more challenging and different processing routes compared to slabs without the code. Firstly, scarfing and cutting need to be done above 200 °C. This is a noticeable factor affecting the production itself because it requires co-operation between the cooling yard inspector and Laha 1 employees to ensure that cutting capacity is sufficient to handle all the slabs from the hood before they cool too much. Secondly, the process order differs in terms of scarfing and cutting. The process route goes through machine scarfing, cutting, possible hand scarfing and transporting to Laha 2 and into charging. Figure 9 presents three potentially congested process steps, which are sampling, machine scarfing and the hydrogen removal furnace in Laha 1. These are determined based on the interviews with the production planning group, development engineer of the slab halls and the employees. Sampling was completed among these groups because they work in a continuous day shift, but naturally, production is not optimized based on their schedule. Another step is machine scarfing, which does not function during night shifts and handles also strip mill mother slabs. Strip mill slabs are typically prioritized higher than plate mill slabs due to large-scale prioritization and strip mill slabs being on the final sequence, unlike plate mill slabs, and thus are not perceived as being so urgent (Production planners, 2021; Slab hall employees, 2021; Tarkka, 2021).

Although the slab hall production is managed by the initial rolling sequence, the slabs are not always finished by the planned sequence. There are several factors affecting the finishing order of the slabs and, based on the interviews, analysing them and their severity is challenging. Some possible reasons are gathered as examples. In some cases, it can be reasonable to handle slabs which are logistically readily available. Crane operators often adjust transportation of the slabs according to their own location in the slab hall (Harju, 2014). Hot cutting capacity is perceived to be one frequently occurring limiting factor. Hot cutting capacity is limited due to the limited number of cooling storage places. Marking the slab numbers after cutting requires a lower temperature so the slabs must be cooled. In addition, the slabs may not be in the absolutely correct order on the initial sequence list in terms of manufacturability. For instance, some process point may be congested but the initial sequence simply defines the desired order. Operators strive to realize this but adaptations usually need to be made. (Production planners, 2021; Slab hall employees, 2021).

4.10.4 Cooling hoods and hydrogen removal furnaces

As Figure 9 presents the material flow, it also shows that hoods and furnaces are placed in different areas. The hoods can be of two types: single- or double pile hoods. Single pile hoods are for slow cooling only. Double pile hoods can be used either for slow cooling of slabs or reheating cold B-code slabs to cutting and scarfing temperatures by loading suitable hot mother slabs into the next pile so the heat transfers into the cold slabs. Hoods and furnaces used for the plate mill's production chain are the following.

Outside:

- Area C with 9 single hoods (CUN1 – CUN9)
- Area M with 6 single hoods (MUN1 – MUN6)
- Area B with 3 double hoods (BUNA – BUNF)

Cooling yard 1:

- 4 single hoods (7UN3 – 7UN6)
- 2 hydrogen removal furnaces with 1-pile capacity each (7UN1 – 7UN2)

Slab hall Laha 1:

- 1 hydrogen removal furnace with 4-pile capacity

The length limits of the hydrogen removal furnaces differ by two meters. The maximum length in the cooling yard 1 furnace is 10 m, whereas Laha 1 is 12 m. A possible material flow challenge related to this came up when interviewing the employees. A possible production restriction may occur if some mother slabs are longer than 10 m. That requires the Laha 1 furnace, which can be already reserved. A parameter change suggestion came up showing that heat planning software would constrain the maximum length of slabs to 10 m so the slabs could be placed into any hydrogen removal furnace. Another point raised in the interviews was that sometimes the strand includes a specific number of mother slabs, of which only a few have to be placed in an "extra" hood. For example, the capacity for 270-mm-thick mother slabs in MUN1 - 6 hoods is 9 pcs. The strand can contain 19 - 20 mother slabs, and therefore a few slabs need to be placed into one extra hood. That amount will not necessarily be enough in that hood, so the cooling yard inspector has to direct more slabs of different heat into the hood. This can contribute to fragmenting of order positions. At the moment, the production planning heat planning software, Lesu, does not take into account the sufficient usage of hoods nor does it strive to optimize the length of mother slabs by furnace maximum length (Paananen, 2021; Slab hall employees, 2021).

4.10.5 Machine scarfing waste

This chapter discusses the strands first heat's first mother slab that is directed to machine scarfing by default. In this context, the slab is called the starting slab. The initiative to become acquainted with the matter came from a plate production planner. The idea was that the starting slab should be planned to be a minimum length stock slab by default. This could potentially save material and machine time and prevent order position fragmentation in the slab halls. Currently, Lesu does not strive to optimize the length of the starting slab to any specific length, but it strives to combinate some order position to the starting slab if possible. This can lead to order position fragmentation if one of the order positions is combinated to the starting slab and the rest are combinated to the other mother slabs. The minimum length of slabs is 4400 mm with a starting scrap of 600 mm, so the planned starting slab can be planned to be 5000 mm minimum length. Machine scarfing requirement class is typically 3, which means that the slab is scarfed once. The other class is 4, which means that the slab is scarfed twice to remove defects. The calculation results are presented in Table 2.

Table 2 Material loss table

Conditionin class 3

Casting mould	Metric weight kg/m	Pcs.	Avg. lenght mm	Material loss factor	Total excess length m	Material loss t
210 mm	2980	613	5872	0,9524	534,54	75,82
270 mm	4095	723	5647	0,9629	467,78	71,07
165 mm	2315	45	5949	0,9429	42,71	5,65
					1045,03	152,54

Conditionin class 4

Casting mould	Metric weight kg/m	Pcs.	Avg. lenght mm	Material loss factor	Total excess length m	Material loss t
210 mm	2980	35	5661	0,9047	23,14	6,57
270 mm	4095	87	5598	0,9259	52,03	15,79
165 mm	2315	1	7909	0,8857	2,91	0,77
					78,08	23,13

Total

Total excess length m	Material loss t
1123,11	175,67

In brief, in 2021 there would have been a total material savings of 175.7 tonnes if the starting slabs were planned to the minimum length. The parameter change to the heat planning software Lesu would be reasonably easy to implement. The overall impact of the parameter change should be evaluated separately and considered in practice. Lesu has multiple parameters, and, therefore, changing one can have unfavourable consequences for wholeness. Based on these results, 175.7 tonnes of material saving would increase the yearly slab amount by 28.8 slabs calculated by their average weight in 2021.

4.11 Plate mill

The plate rolling mill's annual production is about 600000 t. The main products' supply conditions are hot rolled, furnace normalized, TM rolled, TM rolled + accelerate cooled, direct quenched + tempered, and direct quenched. Customer plate supply dimensions are the following: thickness 4.7 - 150 mm, width 800 - 3250 mm and length 2000 - 23000 mm (SSAB, 2018a).

The plate rolling production started in 1967 in SSAB Raahe. The plate rolling line extension began its operation in 1976. There are three cutting options for hot rolled plates at the cold end of the line: mechanical, flame and plasma cutting. Originally the line was designed so that loads are 50 % mechanical and 50 % flame and plasma combined. Nowadays the annual production is about 600000 tonnes, which consists of 200000 tonnes of mechanical, 250000 tonnes of flame and 150000 tonnes of plasma cut plates. This is due to the increased demand for premium products which demand precision cutting (like plasma). One example of a growing demand for premium products are plates designed for laser cutting (SSAB, 2018a; Karjalainen, 2021).

The plate mill line can be divided into two sections: the hot end and the cold end. The hot end contains all the processes and operations done before the hot rolled plates are cooled in the cooling banks where the cold end starts. The hot end includes the pusher type furnace, plate mill, quenching module, hot levelling and normalizing furnace 1 along with different meters. The cold end consists of a larger scale of different operations and routes, for example, marking, crop shear, cold levelling, normalizing furnace 2 and all three cutting options presented previously. The process points and the route of material is presented in Figure 3.

There are two possible routes from the hot end to the cold end, starting from transfer level 1. A straight track leads to cooling bank 2 and 3. Typically, thick plates are placed into cooling bank 3 because they have a longer cooling time. Cooling bank 2 is used for other plates under a certain thickness limit. The other route to the cooling banks is through normalization furnace 1. Normalization furnace 1 has 80 t/h capacity and it usually operates thinner plates to be normalized, tempered or annealed. Normalization furnace 2 located in the gas cutting area handles thicker plates. After cooling, the plates are cold marked by painting and sometimes they are also stamped. The following process step is sample cutting and cropping, where both ends of the plate are cut if possible. The cropping unit cannot crop plates with too much thickness or strength. After cropping, the transfer level 3 divides plates into a gas cutting area or into a mechanical cutting line. The mechanical cutting line consists of a rotary shear, mechanical chopping, piling unit and cold levelling. At the end of the mechanical line is the plasma 8 cutter. Plasma 8 handles premium laser plates and other hand-packaged or VCI-protected products.

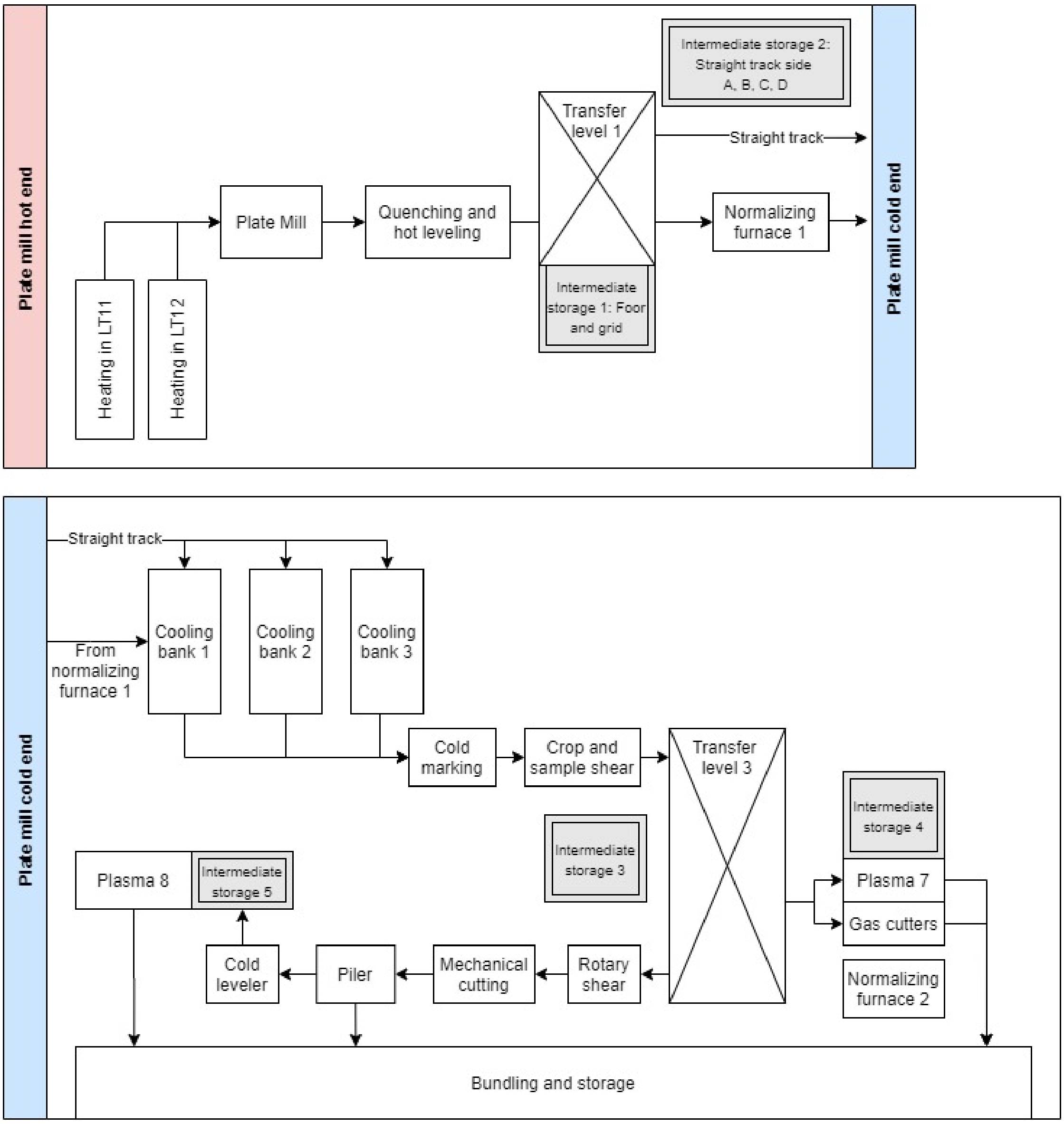


Figure 3 Plate mill's material flow routes.

4.11.1 Plate mill's intermediate storage and cutting lines

There are multiple intermediate storage units located by the plate mill line, all of which serve a slightly different purpose. Intermediate storage 1 and 2 in Figure 9 are for plates headed for normalization, tempering or other furnace treatment. Straight track side A, B, C and D are intermediate storage units that usually contain plates with different routing codes, and which are transported into these piles for different reasons. The reasons for transporting the plates into straight track side piles vary between shifts. The main reason is to store the plates to be furnace treated. Another reason for the usage of the storage unit is to prevent the plate mill from ceasing. Some shifts prefer avoiding the use of the side piles and some shifts generally lift plates to side piles depending on the current production situation. Currently, there are no general work instructions for controlling and managing this intermediate storage. There are some recognized downsides of using the side piles A, B, C and D:

- The piles are basically first in, last out.
- The time of unloading the piles is uncertain.
- Samples are taken only at the future process points during plate ends cropping.
- Order positions can be fragmented, which has effects on the security of supply.

Intermediate storage 3 is usually used for handling large amounts of quenched high-strength steels because cold levelling is typically the bottleneck in that situation. The cold levelling unit is at the end of the line so it can congest process steps before it. Using storage 3 enables the previous functions like cold marking and cropping.

Intermediate storages 4 and 5 are for gas and plasma cutting lines 7 and 8. On the east side of the gas cutting area is a plasma cutter, two gas cutters, a weighing transfer crane and the normalizing furnace 2. On the west side of the area are the strip line's manipulator, ultrasound inspection and three gas cutter units. Gas cutters 1, 2 and 4 are used to cut plates up to 150 mm of material thickness and more complex shapes. Plasma cutter 7 usually cuts thin special products like high-strength direct quenched or tempered plates from normalizing furnace 1. Plasma cutter 7 can also handle thicker plates. Gas cutter 6 is located next to the plasma cutter and it can cut plates up to a material thickness of around 60 mm. Gas cutter 5 cuts normalized plates in normalization furnace 2, and other thicker plates. As mentioned above, plasma cutter 8 is located at the end of mechanical cutting line after the cold levelling unit (Kuisma, 2018).

4.11.2 Plate mill's production control

As shown in Figure 8, the final sequence gives the basis for the plate mill line. Plate rolling is planned to operate based on the final rolling sequence, which is planned within commonly agreed rules and constraints, even though the plate mill's rolling operators can manually change the rolling order and unload the other pusher type furnace faster than originally planned. From the point of view of the plate rolling operators, this action is done to even out production because the planned final rolling sequence contains slabs that cause congestion in later process steps, like in normalization furnace 1. From the viewpoint of production planning, this action does not have a significant effect on the wholeness of sequence planning. Production planning or plate mill work management does not follow whether the plate rolling sequence is realized exactly as planned or not. The following operations in the plate mill are controlled by operators and work management. Indications of congestion or some other restriction in the plate mill can be taken into account in production planning by making changes to current strand planning and the initial rolling sequence. Congesting a cutting line or some treatment unit's mechanical fault, for instance, is one indicator that production planning needs to react to balance the situation. Detection of congestion from historical data due to production planning activities has proven to be challenging. Therefore, there are a few common production planning-related congestion examples presented in chapter 6.1.

Plate rolling mill line processing units are along a long line, and congestion of one unit can cause material shortages after that process step. Physically, the material usually flows through the processing units even if no action is taken at that point. Maintenance resources are limited and sometimes faults occur for various reasons. From the point of view of the plate mill production manager, the most beneficial loading model would be loading the plate mill to the fullest level with an evenly varied final rolling sequence (Karjalainen, 2021).

4.12 Stock slab level

In this case, the factory has defined low stock slab level based on the sum of strip and plate slab levels. That includes strip and plate secondary quality slabs, research work slabs, stock mother slabs, stock slabs and slabs combinated according to customer orders. Stock slab level is defined as low when the total amount of slabs is under 100 kt. The slab level is considered critically low when the total amount is under 80 kt. The slab level is planned to vary in cycles of one year. It is at the highest after the strip mill's annual maintenance break and continuously decreases during the year. In periods of high demand, the factory has bought slabs to compensate for its own slab production capacity. The total number of slabs for the plate mill line has decreased following the merger of Rautaruukki and SSAB in 2014. The distribution and number of slabs is presented in Figure 25. The figure shows finished slabs, unfinished, and normal stock slabs. In addition to these, there are slow-moving stock slabs, slabs of secondary quality, unsalable and stock slabs manufactured for annual maintenance, which together with the above, form the total number of slabs shown in the figure in the line diagram. For the first 6 months of 2021 the factory operated with the lowest total slabs since the merger.

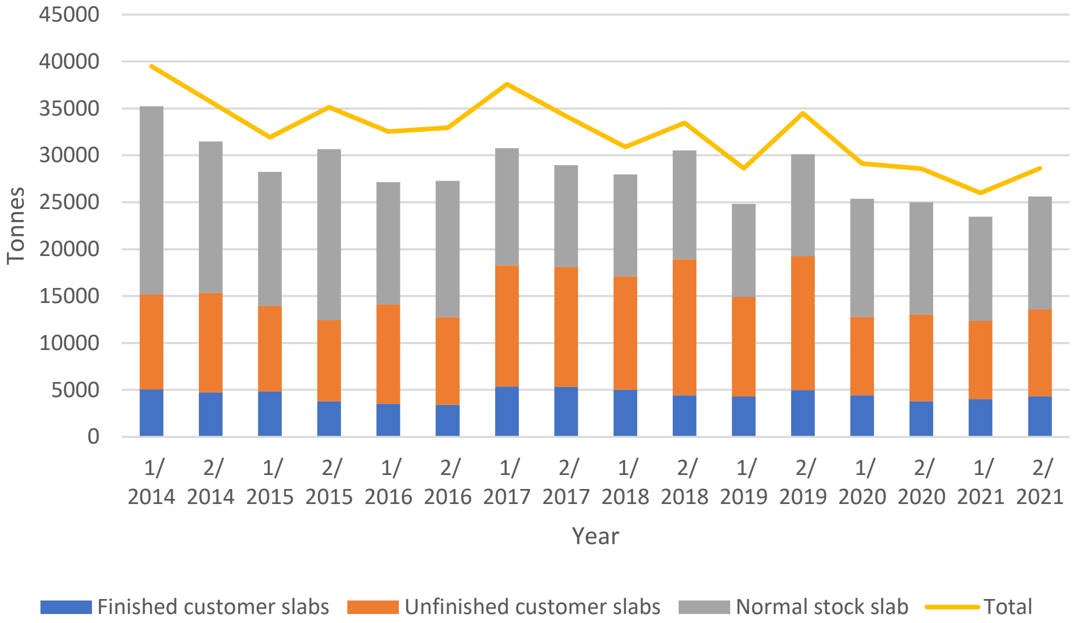


Figure 25 Slab distribution averages semi-annually for plate mill.

The total slab level has decreased over the past years, especially after the merger of Rautaruukki and SSAB in 2014. The reduction in slab level has probably had advantages, but production has still encountered some issues that are perceived to be related to the low slab level. Perhaps the continuous reduction of slab levels initiated the need for this study. It can be seen from Figure 26 that the number of finished slabs stays relatively unaltered, whereas the number of unfinished slabs varies more, but the number still remains fairly constant in linear relationship.

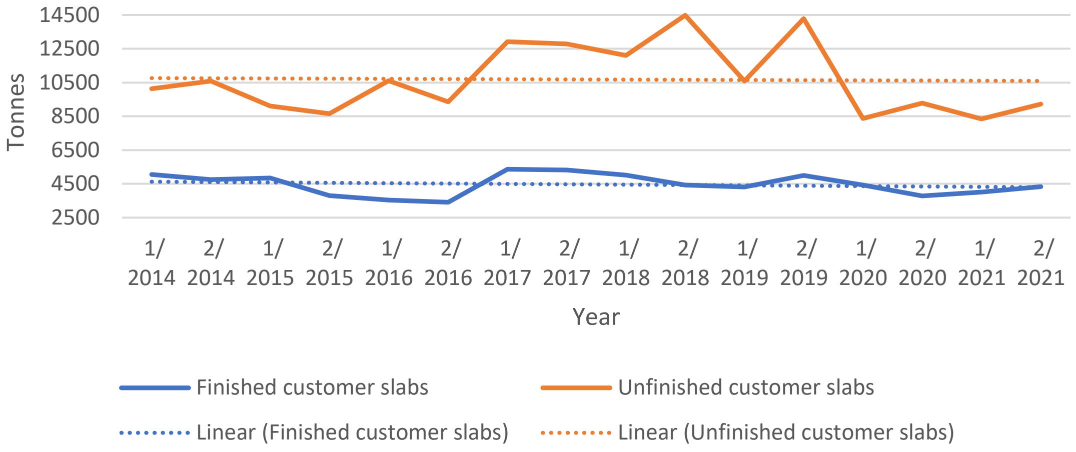


Figure 26 Number of finished and unfinished slabs semi-annually.

The reduction in total number of slabs is at least partially explained by the reduction of normal stock slabs as seen in Figure 27. A considerable amount of capital and value added is also tied up in the stock slabs. Slab storage is a significant intermediate warehouse for production. It involves a large amount of capital consisting of all the raw materials used for the slabs and the added value of processing. The factory slab stock mainly represents two types of stock: production warehouse and backup warehouse. The features of the process warehouse are represented, for instance, by slow cooling in hoods and treatments in the slab halls. In other words, most of the process warehouse slabs are combinated to order position. The characteristics of the backup warehouse, on the other hand, are represented by the capacity of the stock slabs without combination to order position. This warehouse supports the production capacity of the steel plant and maintains a better security of supply (Helaakoski, 2016).

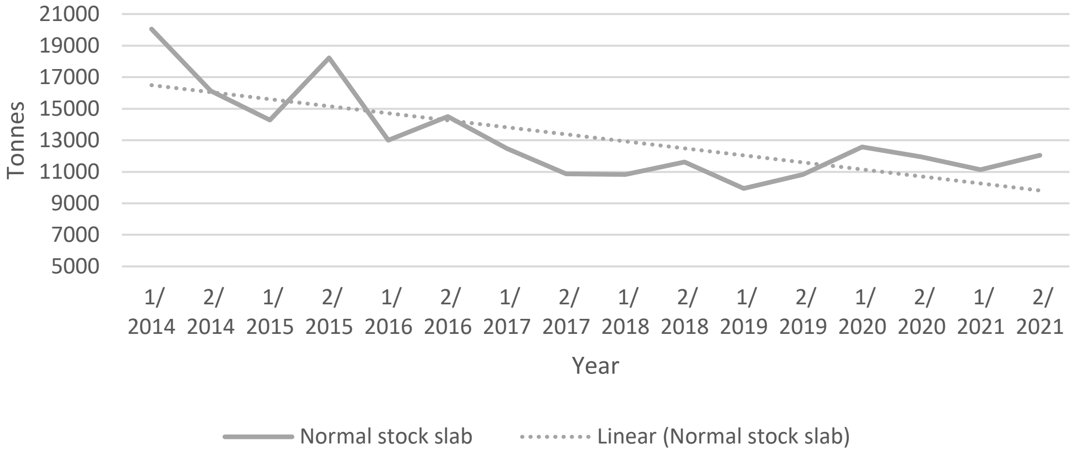


Figure 27 Number of normal stock slabs.

4.13 Production figures & indicators of success

This section discusses the production metrics of 2021. As mentioned above, during the first half of 2021 the factory was operating at the lowest total slab amount since 2014. As can be seen from Figure 29, during the weeks 4 to 14 the factory operated with under 25000 tonnes of slabs. Annual maintenance of the plate rolling mill occurred during weeks 33 and 34, so these weeks should not be reviewed. Figure 29 points out that there is a strong weekly variation among slabs combinated to customer orders. The main factors affecting the number of customer-combinated slab levels are consumption of the plate mill and the supply of the steel plant. Equally important is the current order backlog.

The rolling production of the plate mill is presented in Figure 28. In 2021, the weekly target was met on 34 % of the weeks. The annual maintenance took place on weeks 33 and 34, so there was not production at all during that time. The plate mill gives its capacity promises and the sales and load planning are performed based on that. The plate mill‘s main target per week is to roll the tonnes promised. In theory, the plate mill line seems to have some characteristics of MBR. Thus, its management follows the metrics of rolled tonnes in a very target-oriented manner.

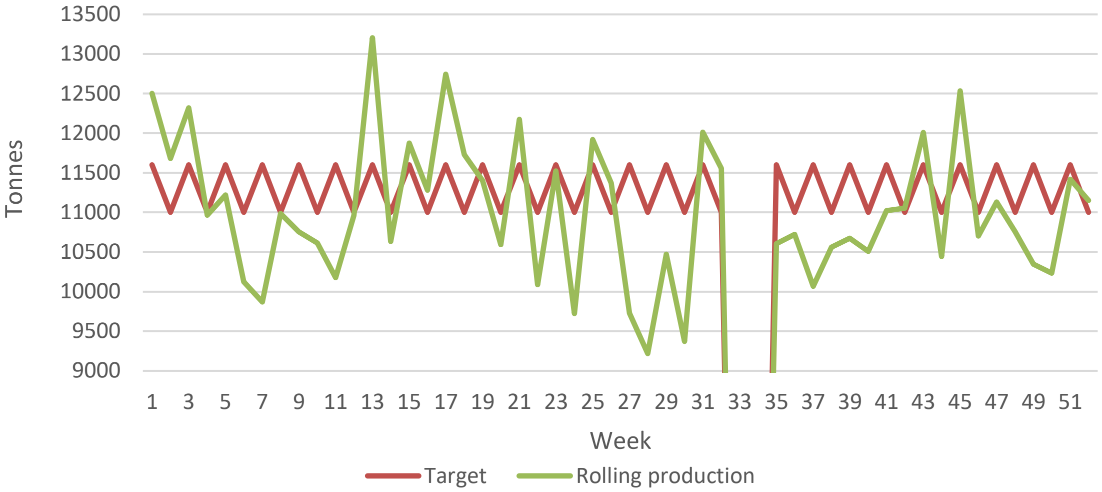


Figure 28 Plate mill production per week in 2021.

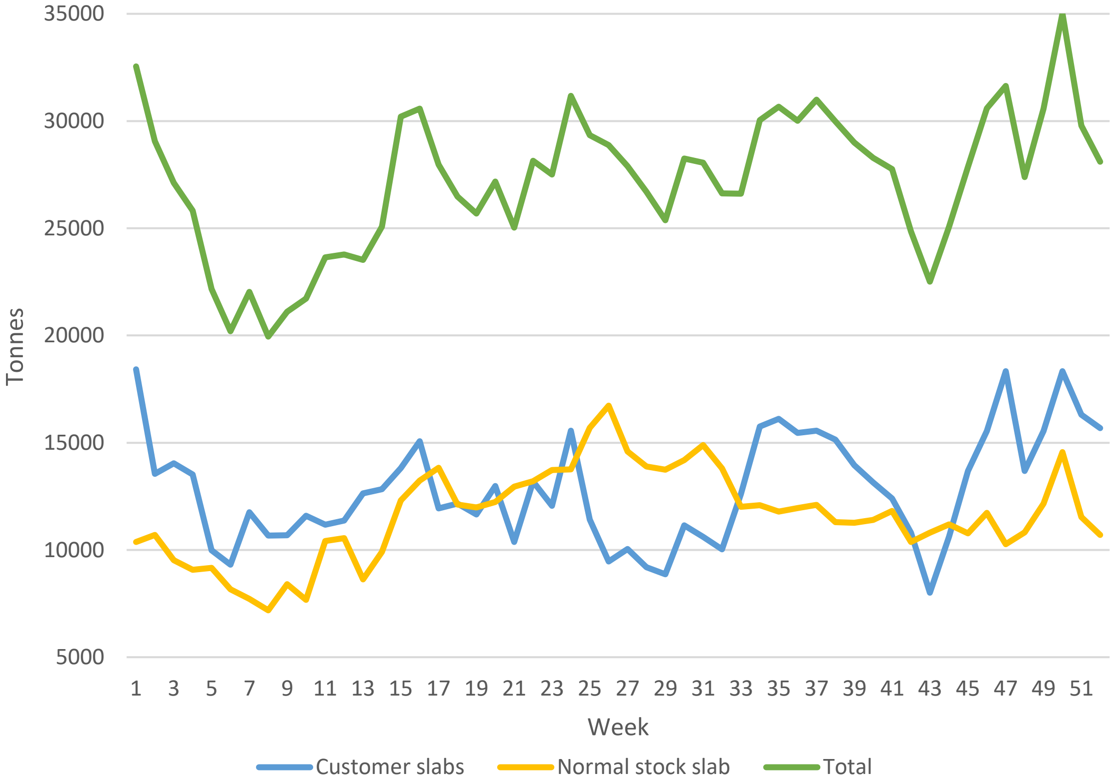


Figure 29 Distribution of slabs in 2021.

It has been noted that the average slab weight is an essential factor in plate mill line rolling production. A higher average slab weigh generally means slabs cast with a thicker 270 mm mould result in a thicker final product. Since the plate mill line measures its production as tonnes and promises its production capacity in tonnes, the higher slab average weight is one factor of success. The slab weight average for each week in 2021 is presented in Figure 30. The connection between the extremes can be seen in Figure 28 and Figure 30. Weeks 13 and 45 are in the top three of plate mill production weeks. The same weeks' average slab weight is also noticeably higher. In addition, a low average weight has had negative effects during the weeks 27 – 30. However, the high or low slab average weight alone does not explain plate mill production figures, since there are some weeks, such as week 48, with a high average weight of 7.11 tonnes and a production level still below the weekly target. Nevertheless, the average slab weight has an indisputable link with the rolling mill results.

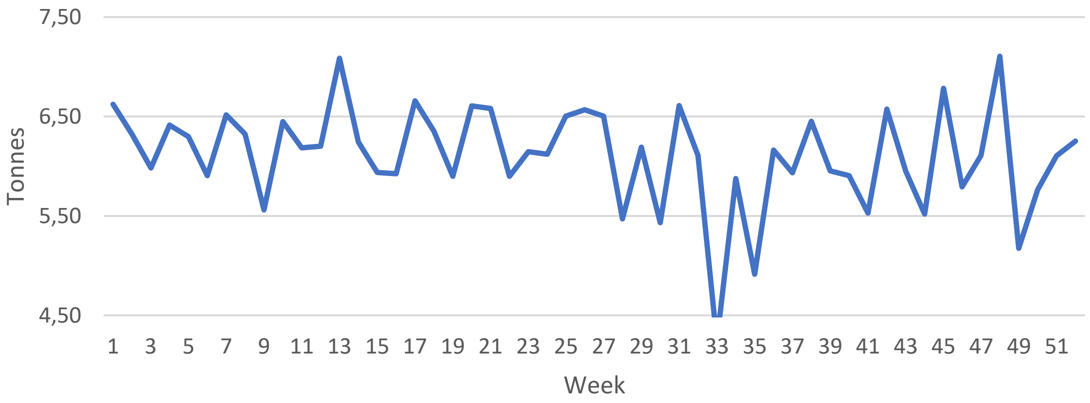


Figure 30 Average weight of rolled slabs per week in 2021.

The cast tonnes for each plate mill per week is presented in Figure 31. As can be seen, the weekly tonnes vary considerably between weeks per each casting mould. This indicates that SSAB Raahe's order backlog is diverse. Some similarities can be observed between Figure 31 and Figure 30. The high casting numbers of 270 mm leads to higher average slab weight in that specific week or the next one, but that is essentially a rough statement, because typically thicker plates are rolled from the 270 mm slabs. High numbers of 270 mm casting thickness do not necessarily lead to high slab average weight. For instance, week 12 270 mm casts will appear as a rolling production result for the following week. The same seems to be repeated for casting weeks 45 and 47.

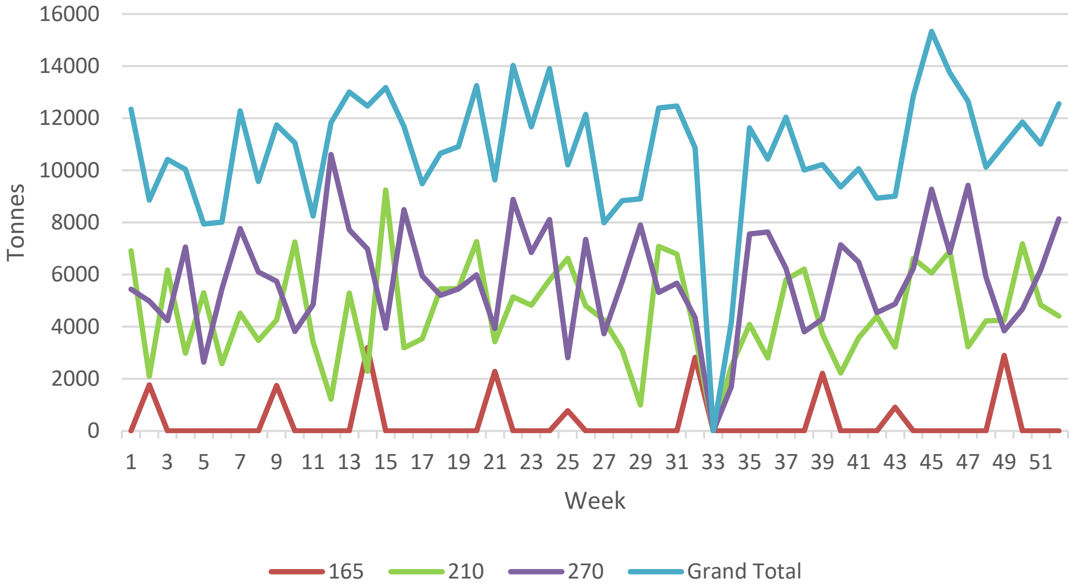


Figure 31 Caster 6 cast tonnes with different moulds per week in 2021.

5 EMPIRICAL RESEARCH

The empirical part of the research started by defining the problem from different aspects and studying the production chain in order to become acquainted with the overall process. Defining the current state became one essential topic. This was followed by several interviews and production data collection. The study interviewed several dozen factory personnel from upper management to operators in production to map out perspectives on the topic at hand. The target of the study slowly took shape when mapping the current state. Identifying problems and describing solutions to issues related to low stock slab level to increase production flow in operating areas under the influence of production planning was the final desired outcome. The improvement suggestions were not intended to negatively affect any production figures and metrics. The data is gathered from the factory's internal production reporting databases. It was discovered that the issues raised in the interviews needed to be broad enough to produce long-term solutions and avoid sub-optimization, which might not have much real impact on the production flow.

6 PROBLEM IDENTIFICATION IN PLATE PRODUCTION

The most typical production planning-related problem in the plate mill line is congestion during some process step. Congestion can happen for a few reasons. There can be mechanical failures, lack of staff or the process step is not capable of handling the amount of a certain product or material at a certain moment. One of the main focuses of this thesis is to identify problems related to production planning's actions; thus, the problems would be under their influence. The following questions was asked: What production planning actions affect the plate mill's material flow and how?

When a certain plate mill's process step is not capable of handling the planned flow of material, there are few options to address this situation. Either they can keep the earlier process steps running by directing plates to intermediate storages (if possible), or cease the production temporarily. When the process step is not capable of handling the amount of material at the time, it means that there is too much load, or the process step is undersized. However, production planning can only affect the planned load and react to the situation.

Plate mill rolling sequence is generally the only and the most important production controlling input that the plate mill gets from the production planning organization. That input is formed by production planning and released to production about three to five times per day. When operating at low stock slab level, it generally means that production planning has fewer options to form the plate mill sequence. The plate sequence gives the basis for material flow in the plate mill line.

6.1 Plate production problems

Concerning the causes of congested process steps, the most common production planning-related root cause to plate production problems is monotonous distribution of slabs planned for plate mill. In practice, this term means “Too much of the same product”. In general, this concerns thin and long plates, direct quenched plates or normalization furnace 1 treatable plates. Multiple people working with the plate mill production chain have identified a few recognizable problem situations related to this root cause. This root cause is involved in the example cases presented next.

Case 1: Thin-rolled slabs from both pusher type furnaces.

This case means that production planning has formed the plate mill's rolling sequence by planning thin-rolled slabs for both pusher type furnaces. These slabs are typically lighter than slabs used on thicker plates. Thin plates are typically long so they reserve more space on the cooling banks. They usually need more cold markings, but they still are not favourable in terms of production tonnes. Sometimes, production planning has raised temperatures in LT11 to the same operating temperature as LT12 and picked some slabs from LT12's initial rolling sequence and moved them into LT11 lists. This action is done to keep both pusher type furnaces running, while knowing that it can cause congesting in some of the plate mill's process steps.

As mentioned before, the plate mill's shifts have the option of lifting the long plates into the straight track's side A, B, C and D piles, thus ensuring the operation of the plate mill. At the moment, production planning does not take a position on the amount or quality of the straight track's side piles.

Case 2: Some of the cutting lines become congested

Case 2 is about gas, mechanical or plasma 7 or 8 congestion. Even though the SCM organization strives to achieve equal loading on each cutting line, somehow one or multiple of them can get congested. For example, the mechanical line gets overloaded. In this situation, the mechanical cutting load can be directed to plasma 8 and try to balance the temporarily raised workload. In this case, production planning gets the impulse to balance the situation with more gas-cut plates.

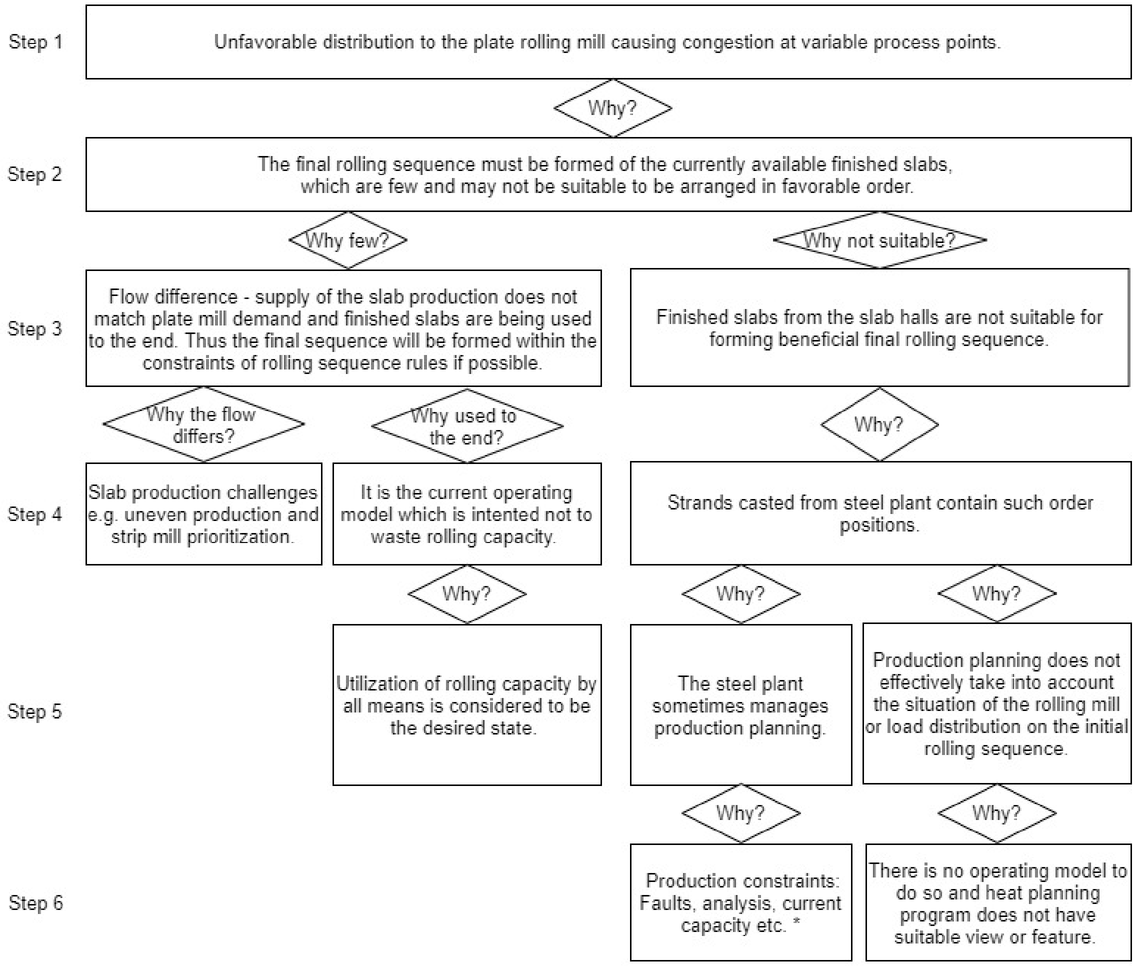
In order to fix the occurred unbalanced production situation, sometimes the production planning needs to form complete heats for another casting mould and wait a minimum of two days to get those slabs into the plate mill's production. Balancing is slow and the situation can change before the correction is complete. So, the actions of production planning are often reactive.

6.2 Problem and root causes

Unfavourable load distribution to the plate mill has been found to be linked to low stock slab level. At least, these two phenomena have been found to occur simultaneously. The following 5x-why analysis is based on several interviews. Analysis in Figure 32 is divided into multiple sub-reasons as it goes further. The root causes found could be called factors influencing the quality of the final rolling sequence. As mentioned in the theory, two sub-reasons are the maximum amount to keep the focus on the relevant issues. Analysis reveals that the problem defined in step 1 is divided into four root causes in steps four, five and six.

The root cause for the scarcity of the finished slabs is the prevailing perception of maximum utilization of rolling capacity and the flow difference between slab production and rolling mill demand. Utilization of the capacity leads to an operating model which is intended to not waste rolling capacity, which is currently being realized by forming the rolling sequence by any means within the sequence forming rules. Even if the final rolling sequence is formed within the rules, it does not mean that sequence would be qualitatively one that flows through the rolling mill line without causing additional congestion. It can be stated that the material flow in the previous process points before the plate mill is not always sufficient to meet the demand of the plate rolling mill. This is the result of several reasons, which are, for example, uneven production and strip mill prioritization.

Unsuitability of the slabs for favourable sequence planning has two root causes. Sometimes the steel plant has production constraints which force it to manage production planning to form strands according to their needs. That root reason is out of the scope of production planning and thus, it will not be discussed any further. As discussed in chapter 4.8, variation occurs in many respects. As can be seen from Figure 13, the prevailing rough estimation that the majority of 270 mm slabs are gas-cut and 210 mm slabs are mechanical-cut is correct. However, the proportion of the non-dominant cutting routes of the 210 mm and 270 mm is significant, and they may cause temporary distortion of the rolling sequence if the correction is made without knowledge of strand contents. Is this information sufficient when planning strands? It seems like production planning does not effectively take into account the situation of the rolling mill or the load distribution on the initial rolling sequence because there is no standardized operating model to do so, and planning software does not have a suitable feature or view for that. Sometimes production planning gets some indication of production issues or restrictions from the plate mill, so production planning activities are reactive. One procedure to balance the distorted production situation is to manage steel production and prioritize strands of a different casting mould.



* Steel plant should not manage production for convenience.

Figure 32 5 x why analysis of the most essential problem of plate mill line

7 PROBLEM IDENTIFICATION IN SLAB TREATMENTS AND LOGISTICS

The interviews with slab hall employees and development engineer showed that the biggest challenges are perceived to be uneven production, transmission of prioritization information and mother slab planning (length and number of pieces).

Uneven production is perceived to have unfavourable impacts on many operations in the cooling yard and slab hall operation zone. From the slab hall point of view, uneven production manifests itself in the occasional uneven utilization of hood capacity and the simultaneous need to perform B-code slabs hot cutting and scarfing. Uneven production temporarily binds the contractor’s logistical resources that might restrict some of its operations. The simultaneous need to load and unload hoods and transport slabs from warehouse areas to slab halls binds the contractor’s resources so that one of several operations may inevitably be delayed. As mentioned in chapter 4.10.1, there are some prioritization information transfer issues between production planning and slab hall employees. There may be differences in prioritization and information transfer between production and production planning, and therefore there appears to be potential for development. The last remarkable issue was the mother slab planning. This considers the slabs with hydrogen removal furnace treatment and slabs with slow cooling in hoods. The maximum length difference in hydrogen removal furnaces may lead to production restrictions. The number of slow-cooled mother slabs may sometimes be unfavourable in terms of hood capacity utilization. All things considered, production planning is able to have an effect on all mentioned matters, but the most significant issue seems to be uneven production. Uneven pace of production can be considered a continuous state with no actual benefits. The rest of the problems can be considered to be much smaller and not so significant overall. For instance, prioritization-related issues can be approached by agreeing on common practices or by software modification to the Jasu sequence planning software that allows slabs to be easily prioritized. Mother slab planning-related issues require parameter changes to the Lesu heat planning software and testing and surveillance in practice.

7.1 Problem and root causes

The 5x-why analysis has been done to address the most essential issue based on the interviews – uneven production of B-coded strands. The analysis is presented in Figure 33, which shows that uneven production is caused mainly by two reasons. The lack of suitable operating model and target-oriented production of the steel plant. As seen in Table 1, the proportion of the B-coded strands varies between 25 - 35 % with an average of 31 %. Thus, the unevenness of the strand production is also reflected in the unevenness of the B-coded strands.

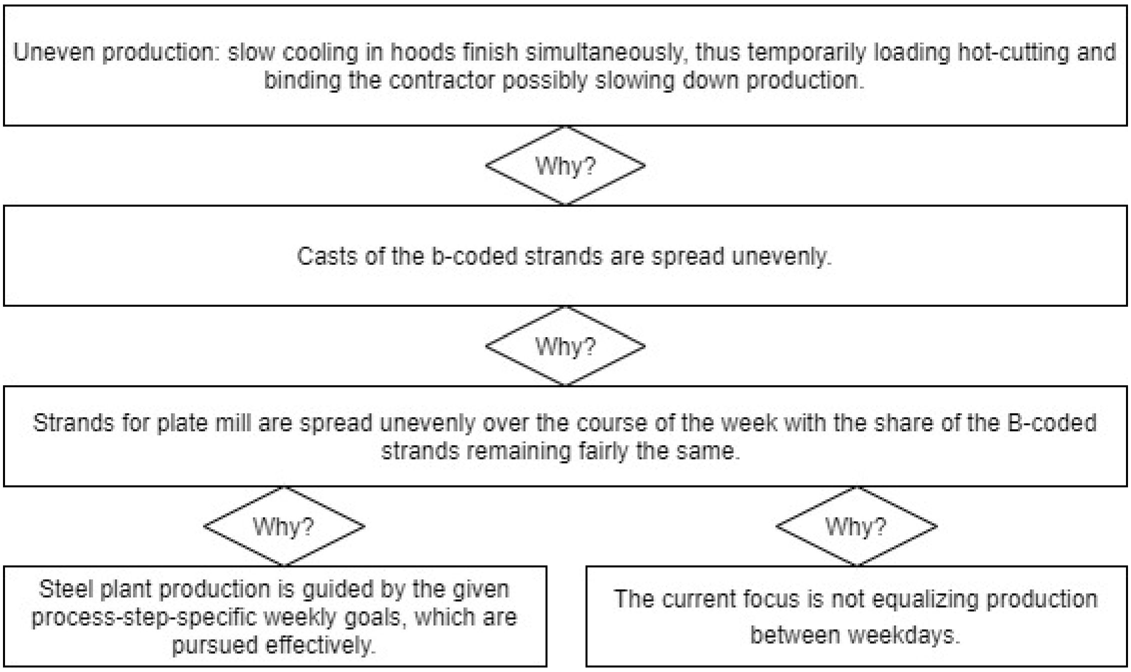


Figure 33 5x-why analysis of slab production's most essential problem.

8 SUGGESTED IMPROVEMENTS

8.1 Improvement suggestions for plate mill flow development

Two of three root causes from Figure 32 are discussed in this chapter because steel plant production constraints are outside the scope of production planning. When managing a steel plant, production planning does not actively take into account the different routes and shares of the unfinished material in the production because software does not have a suitable feature for that. Additionally, there is not a work instruction to do so. A need has been identified or the necessary additional information to support production planning. Currently, production planning may not have a proper view of the overall production situation and knowledge of the share of slabs with different process routes in the plate mill. The idea of a software add-on arose, whose properties are described below.

As mentioned, the scarcity of finished slabs is due to the current operating model, which actually is not standardized in any way. The current operating model has gradually taken shape. One drawback in the current operating model is that production planning has fewer options to respond to variable restrictions or production constraints. However, it should be noted that the slabs will not necessarily be finished from the slab hall in accordance with the page number order. In summary, this operation model restricts the production planning capacity to operate. There has been some discussion with the production planners about the possibility of jointly determining a lower limit for the number of finished plates on the initial rolling sequence.

The suggestion to improve plate mill flow is to approach the problem from these two aspects: planning and describing a suitable add-on for the planning software and outlining a new operating model that defines the minimum level for finished slabs. The targets of these actions are producing useful additional information and increasing the ability of production planning to anticipate production problems. The end result should be an increased ability of production planning to better control production and create a rolling sequence that has better qualifications to flow through the plate mill line without additional congestion.

8.1.1 Add-on for planning software

Experience in production planning and interviews with current production planners provides the basis for defining requirements and outlines for the add-ons. The add-ons are planned to be separate in the heat planning software Lesu and sequence planning software Jasu. Both are required to be simple and easy to read. The most essential feature for Jasu would be the view of the current intermediate storage levels at different process points in the plate mill line and the ratios and quantities of slabs with different routings. The feature for Lesu would be a view that enables inspection of the contents of the planned strand for better adaptation to the current production situation. The draft for the add-on for Jasu is presented in Figure 34. It shows both pusher type furnaces separately and the shares of material at each process step. The essential feature would be the visual graph which shows realized shares in production in tonnes, because manufacturing capacities are expressed in tonnes. The plate mill intermediate warehouse loads should also be visible. If necessary, a third bar can also be added to describe the status of the intermediate storage in the plate mill line.

LT 11

	Laser t	DQ t	Tempering t	Normalization t
165				
210				
270				
	Tot.	Tot.	Tot.	Tot.

Process	pcs.	%
090		
096		
552		
530		
554		
580		
915		

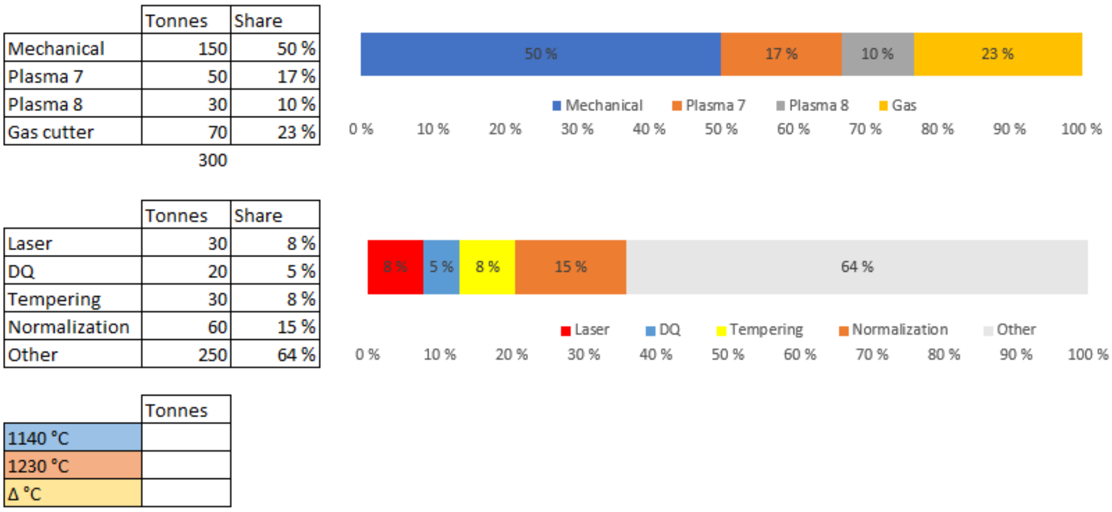
LT 12

	Laser t	DQ t	Tempering t	Normalization t
165				
210				
270				
	Tot.	Tot.	Tot.	Tot.

Process	pcs.	%
090		
096		
552		
530		
554		
580		
915		

Figure 34 Draft for Jasu.

Being able to review the content of the planned strand is the main characteristic of the view for Lesu. The draft is presented below in Figure 33. The essentials are presented again in the bars. The initiative of adding the 1140 °C and 1230 °C temperatures to the draft came from one production planner. The information about the pusher type furnace shares would help to keep furnace loads in balance.



	Tonnes	Share
Mechanical	150	50 %
Plasma 7	50	17 %
Plasma 8	30	10 %
Gas cutter	70	23 %
	300	

	Tonnes	Share
Laser	30	8 %
DQ	20	5 %
Tempering	30	8 %
Normalization	60	15 %
Other	250	64 %

	Tonnes
1140 °C	
1230 °C	
Δ °C	

Figure 35 Draft for Lesu.

8.1.2 The outlining of new operating model

The idea of the new operating model is to define a level for finished slabs and continue production by keeping the desired levels. Better conditions for material flow are made possible by increasing the intermediate storage of finished slabs to enable more efficient sequence planning. The increased intermediate storage would be a strategic buffer to absorb and reduce the variation in slab production. In addition, the rules for intermediate storage (straight track side) should be formed. That could be seen as standardization, which is Lean work. Overall, production planning should be seen as responsible for the plate mill throughput with the work management. By standardizing plate mill operations, production planning would get feedback about the quality of the final rolling sequence. Development of the operating model could be seen as a kaizen event which is one step in continuous improvement.

8.2 Improvement suggestion for slab treatments and logistics

Based on the 5x-why analysis presented in Figure 33, the simultaneous completion of B-coded strands causes problems. There appears to be two root causes for this occurrence. The steel plant's weekly targets are pursued so efficiently that the remaining casting capacity for the plate mill is often much less at the weekends. In addition, the casting production for the whole week has not been strived to level on weekdays. The improvement suggestion is simple: new work instructions for levelling the production. It is assumed that the share of B-coded strands will level off as the whole weekly production levels off. This might also have an effect on the timeliness of cast order positions as the production planning ability to take into account new order positions at the end of the week's production increases. Based on this theory, levelling (Heijunka) is one fundamental aspect of Lean thinking. The illustration of Kingman's equation (Figure 2) shows that with higher variation, the lead time increases. The unlevelled load of casts can be seen as a source of variation which contributes to queue lengths.

9 DISCUSSION AND CONCLUSIONS

It quickly became apparent that measuring production planning-related production problems and evaluating the effects of improvement suggestions are problematic. It was difficult to detect production planning and low slab level-related issues from the historical data. In addition, the severity of issues raised from the interviews is challenging to observe afterwards. Therefore, case study was chosen as the research approach. The study included dozens of interviews throughout the production chain, production planning and steps before production planning.

In terms of production flow, the importance of the *right* production seems to be emphasized as the slab level goes low. What does the right production mean? It could be stated as the most optimum control of slab production to ensure the formation of the most favourable final plate rolling sequence. There are a few factors affecting negatively on rolling sequence quality in terms of throughput. A steel plant's restrictions occasionally direct slab manufacturing and the completion order in slab halls does not always follow the initial sequence. The improvements suggested in this thesis for production planning's capabilities to balance a distorted rolling sequence are considered a valued contribution. When it comes to the plate rolling line, the shifts should not have different ways of utilizing the intermediate storages. In general, the plate mill work management and operators are responsible for the throughput of the given rolling sequence, and production planning has a little bearing on it.

To summarize, when production planning has fewer options for forming the initial rolling sequence, the probability of unnecessary congestion increases. As a result of the 5x-why analysis, the ability of production planning to prioritize the right strands needs to be expanded to raise the prerequisites and form the most favourable sequence. The improvement suggestion to meet this requirement is proposed to be achieved by the add-on to the planning software. Another option to increase the number of planning options would be the outlining of a new operating model, which defines the strategic buffer for finished slabs so that the slabs would not be used to the end. Both of these actions are considered to increase the flow and throughput. The impacts of the suggested improvement proposals on the overall throughput have not been calculated as the suggestions are relatively comprehensive. The effects can be evaluated over time.

One topic for further research would be the dependence of the production capacity of the rolling mill on the product mix. In other words, in which cases the plate mill line has the capacity to produce the promised tonnes and in which cases the product mix constrains it. An additional area of study could be whether the product mix has changed over the years and if so, how it has affected the plate mill line's production capacity.

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