

JOAKIM STORCK

STRATEGIC AND OPERATIONAL
CAPABILITIES IN STEEL PRODUCTION



**KTH Industrial Engineering
and Management**

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CAPABILITIES IN STEEL PRODUCTION**

PRODUCT VARIETY AND PERFORMANCE

JOAKIM STORCK

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KTH School of Industrial
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Department of Production Engineering
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ABSTRACT

Steel producers that employ niche market strategies are continuously seeking to reduce production cost while maintaining a diverse product mix. The business model is typically based on marketing of high-strength special or stainless steels. However, the desire to avoid direct cost competition is over time gradually leading towards increased product variety and smaller order volumes (tonnes per order) for each product.

This thesis analyses how production cost is linked to product variety in steel strip production. Results are based on new models for assessment of opportunities for performance improvement in high product-variety steel production.

The need for flexible production processes increases with increasing product variety. Operational capabilities linked to process flexibility determine the extent to which steel producers can eliminate in-process inventory and accomplish close coupling between process steps. Niche market producers that invest in process flexibility improvements can lower production costs both due to reduced work-in-process and lower energy consumption. An additional benefit is reduced environmental impact.

The following problems are addressed:

- Development of a method to assess the influence of product variety on performance in steel production.
- Development of models of continuous casting and hot rolling that account for product variety and cost effects with consideration of varying degrees of process flexibility.
- Development of a strategy process model that focus on the strategic value of operational capabilities related to process flexibility.

Investments in operational capabilities regarding process flexibility have a strategic impact. An appreciation for the effects of process flexibility should permeate the organisation's daily work since the accumulated contribution of many, seemingly unimportant, incremental changes significantly influences the strategic opportunities of the company.

SAMMANFATTNING

Stålproducenter med nischmarknadsstrategier försöker ständigt sänka sina produktionskostnader samtidigt som en varierad produktflora bibehålls. Affärsmodellen bygger i typfallet på försäljning av höghållfasta specialstål eller rostfria stål. Strävan att undvika direkt priskonkurrens leder dock med tiden gradvis till ökad produktvariation och mindre ordervolymer (ton per order) för varje produkt.

Denna avhandling analyserar hur produktionskostnaden är kopplad till graden av produktvariation vid tillverkning av band. Resultaten bygger på nya modeller för utvärdering av förutsättningarna för prestandaförbättring i stålindustri med stor produktvariation.

Behovet av flexibla produktionsprocesser ökar med ökande produktvariation. Praktiska förmågor kopplade till processflexibilitet avgör till vilken grad ståltillverkare förmår att eliminera mellanlager och åstadkomma en tät koppling mellan processteg. Nischmarknadsproducenter som investerar i förbättrad flexibilitet kan sänka sina produktionskostnader både genom minskad mängd produkter i arbete och reducerad energiförbrukning. Detta medför också minskad miljöbelastning.

Följande problemställningar adresseras:

- Utveckling av en metod för att utvärdera inverkan av produktvariation på prestanda vid ståltillverkning.
- Utveckling av en modell för stränggjutning och varmvalsning som tar hänsyn till produktvariation och kostnadseffekter för olika grad av processflexibilitet.
- Utveckling av en strategimodell som fokuserar på det strategiska värdet av operativa förmågor kopplade till processflexibilitet.

Investeringar i operativa förmågor vad avser processflexibilitet är av strategisk betydelse. Förståelse för betydelsen av processflexibilitet bör genomsyra det dagliga arbetet eftersom det samlade bidraget av många, till synes obetydliga, små förändringar har en avgörande inverkan på företagets strategiska förutsättningar.

PUBLICATIONS

Some ideas and results presented in this thesis were previously published in scientific journals, at scientific conferences and elsewhere as indicated below.

Peer-reviewed scientific journals

- i J. Storck, "Exploring improvement trajectories with dynamic process cost modelling: a case from the steel industry". Accepted for *International Journal of Production Research*, 2009.
Appears as [79] in this thesis.

Peer-reviewed scientific conferences

- ii J. Storck and B. Lindberg, "A lean production strategy for hot charge operation of a steel mill", *Proceedings of the IET International Conference on Agile Manufacturing (ICAM'07)*, 158–167, Collingwood College, Durham, U.K., 2007.
Appears as [82] in this thesis.
- iii J. Storck and B. Lindberg, "Assessment of best scheduling practice in continuous casting and hot rolling of stainless steel strip by system dynamics simulation", *Key Engineering Materials: the 12th International Conference on Sheet Metal (SheMet'07)*, 344:897–904, 2007.
Appears as [80] in this thesis.
- iv J. Storck and B. Lindberg, "A cost model for the effect of setup time reduction in stainless steel strip production", *Proceedings of the 1:st Swedish Production Symposium*, Göteborg, 2007.
Appears as [81] in this thesis ¹.
- v J. Storck and B. Lindberg, "A dynamic cost model for the effect of improved process flexibility in steel plants", *Manufacturing systems and technologies for the new frontier:*

¹ An earlier version of this paper was presented at Stål 2007, Borlänge, April 2007.

the 41st CIRP conference on manufacturing systems, 45–50,
Springer, London, 2008.
Appears as [83] in this thesis.

Other publications:

vi L. Bentell, J. Storck and S. Ekerot, “Just-in-timelegering av stål”, *Bergsmannen*, 2:44–45, 2008. Appears as [5] in this thesis.

*Take care that your style and diction run musically, pleasantly,
and plainly, with clear, proper, and well-placed words,
setting forth your purpose to the best of your power,
and putting your ideas intelligibly, without confusion or obscurity.*

— Miguel de Cervantes Saavedra, *Don Quixote*, 1605

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The words of Cervantes may sound like plain common sense, but it was never straightforward to go from vague ideas to a clearly formulated vision of what this thesis would be. This work is my own, but I met and worked with many people who helped me on the way, and to whom I have reason to express my gratitude.

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Falun, November 2009.

CONTENTS

Acronyms xiv

I THESIS 1

1	Introduction	3
1.1	Main objectives and assumptions	3
1.2	Research questions	4
1.3	Contribution of thesis and appended papers	5
1.4	Disposition	7
2	Steel production	9
2.1	Process description	9
2.1.1	Overview	9
2.1.2	Steelmaking	10
2.1.3	Slab conditioning	12
2.1.4	Hot rolling	12
2.2	Strategic considerations	15
3	Strategy	17
3.1	What is strategy?	17
3.2	The strategy process	19
3.3	Market requirements	21
3.4	Capabilities	22
3.5	Production control	24
3.5.1	Order coupling policy	24
3.5.2	Control mode — “push” versus “pull”	25
3.6	Flexibility	27
3.7	Summary	28
4	Methodological framework	29
4.1	Model based strategy support	29
4.1.1	The capability gap	29
4.1.2	Improving capability awareness	31
4.1.3	The five-step framework	32
4.2	Simulation	34
4.2.1	Nature of simulation models	34
4.2.2	Simulation paradigms	35
4.2.3	Model testing	36
4.3	Process cost modelling	37
4.4	Capability assessment	38
4.4.1	Use of process-based cost models	38

4.4.2	Exploratory approach	39
4.4.3	Capability requirements analysis	40
4.5	Comments	42
5	Modelling steel production	43
5.1	Model structure	44
5.2	Slab production and order processing	46
5.2.1	The production control loop	46
5.2.2	The caster operation and scheduling loops	47
5.2.3	The WIP control loop	50
5.2.4	The backlog adjustment and order fulfilment loops	51
5.2.5	Customer orders	53
5.3	Modelling product variety	54
5.3.1	Product groups	54
5.3.2	Fraction setup	57
5.3.3	Fraction ordered material	59
5.4	Slab reheating and hot rolling	60
5.4.1	The scheduling operation loop	61
5.4.2	The furnace control loop	63
5.4.3	The hot charging loop	63
5.4.4	The HRM operation loop	64
5.4.5	Roll wear and roll changes	65
5.5	Summary	66
6	Simulation analysis and results	67
6.1	Overview	67
6.2	Initial results	67
6.3	Influence of product variety	68
6.3.1	Delivery delay	69
6.3.2	HRM setup time	71
6.3.3	Charge weight	74
6.3.4	SCC setup time	76
6.3.5	Charge weight and SCC setup time	78
6.3.6	HRM setup, small charges and rapid SCC setup	80
6.4	Synthesis	82
6.5	Summary	85
7	Discussion and future research	87
7.1	Research questions revisited	87
7.2	RQ ₁ — Assessment method	88
7.3	RQ ₂ — Effect of product variety	90
7.4	RQ ₃ — Implications for strategy formation	92

- 7.5 Concluding remarks 94
- 7.6 Critical review and future research 99

II APPENDICES 103

- A Equations for the slab cooling and reheating model 105
 - A.1 Furnace power 105
 - A.2 Furnace capacity 108

REFERENCES 111

INDEX 121

III APPENDED PAPERS 127

- I Paper i 129
- II Paper ii 151
- III Paper iii 163
- IV Paper iv 173
- v Paper v 183
- VI Paper vi 191

ACRONYMS

AOD	argon oxygen decarburisation.	9, 10
ATO	assemble to order.	24, 25
CAQC	computer aided quality control.	12, 95
CC	continuous casting.	6, 9, 10, 24, 26, 55, 74, 83, 95, 96
CLD	causal loop diagram.	7, 39, 46, 50, 60
CODP	customer order decoupling point.	24
DE	discrete event.	35
DES	discrete event simulation.	37
DFA	design for assembly.	101
DPCM	dynamic process cost modelling.	6, 7, 29, 32, 34, 38, 42, 43, 66, 88, 89, 93, 99, 100, 105
EAF	electric arc furnace.	9, 10
EDA	exploratory data analysis.	6, 38, 40, 99
ETO	engineer to order.	24, 25
FIFO	first in/first out.	63
HRM	hot rolling mill.	6, 9, 11, 24, 26, 44, 55, 61, 64, 65, 67–69, 72, 74, 82, 83, 91
JIT	just-in-time.	3, 4
LF	ladle furnace.	9, 10
MTO	make-to-order.	24–26, 52
MTS	make-to-stock.	24
MTS-MTO	make-to-stock/make-to-order.	25, 26
RBV	resource based view.	18
SCC	steelmaking—continuous casting.	10, 25, 69, 78, 85, 88
SD	system dynamics.	6, 29, 31, 32, 34–37, 39, 66, 89, 107
SMED	single minute exchange of dies.	3, 4, 23, 28, 92
TBPT	time between production times.	59, 60, 83
TPS	Toyota production system.	4, 20
WIP	work-in-process.	6, 16, 25, 26, 62, 67, 72, 85, 86

Part I

THESIS

INTRODUCTION

1.1 MAIN OBJECTIVES AND ASSUMPTIONS

The capability to produce the quality and quantity currently in demand is necessary for any steel producer. However, it is particularly important for niche producers of stainless and special steels since their customers often order small quantities of highly value-added products at infrequent intervals. Specialisation towards high-end special grades has been a successful strategy for Swedish steel producers for many years. However, competitors gradually move into areas that were once part of the special-steel niche. Successful products become subject to price competition, and current market leaders are therefore continuously seeking to reduce cost and develop new attractive products.

Hence, differentiation within special steels is a way to avoid direct price-competition and charge premium prices, but it comes at the cost of increased complexity in production when a large number of different product variants are made in the same plant.

Surprisingly little research on the steel production system is reported in the literature. The aim of this thesis is to analyse how production cost is linked to product variety in diversified high-end steel strip production. In particular, the opportunities for cost reduction in the case of high product variety is analysed. It is shown how a typical steel plant has been designed for efficient high-volume production, and that other operational capabilities are required for low-cost high-variety production under a niche-market strategy. At the same time it is shown that diversified low-cost steel production is possible if the "right" operational capabilities are developed. The special requirements for cost reduction under a niche market strategy must therefore be recognised and targeted in the firm's long-term strategy.

Different kinds of flexible production systems have been developed to cope with low-cost, high-variety production in other industries. Flexible processes is what makes just-in-time (JIT) manufacturing work. This was recognised by *Shigeo Shingo*, who developed the single minute exchange of dies (SMED)-method in

the late 1950's and early 1960's [70, p.xxii]. SMED was implemented at Toyota by *Taiichi Ohno* at that time [56]. Ohno pioneered the development of the Toyota production system (TPS), which eventually led to the emergence of for example the *lean production* paradigm [96, 36].

The main idea put forward in this thesis is this. Just like flexible processes are central to JIT production, they determine the extent to which steel producers can eliminate in-process inventory and accomplish close coupling between process steps. Improved process flexibility improve productivity since less resources are needed in production. The need for flexibility increases with increasing product variety. A niche steel producer that improve the flexibility of its processes may thus simultaneously reduce production cost and environmental impact.

Implementation of flexible processes is not free; it requires investment in manufacturing capabilities in the form of new or modified equipment, and often in the form of organisational skills that improve the flexibility of operations within a plant. In either case, the new, flexible, processes come at a cost – ultimately the construction of an entirely new plant. It is the responsibility of firm management to adopt a strategic perspective on production and employ the necessary changes to align capability requirements of business strategy and operations.

This thesis contributes to knowledge in three areas. One is *methods* for assessment of the influence of product variety on performance in steel production. Another is *models* that describe the steel production system and that incorporate product variety. A third area of contribution is *strategy*, and concerns the nature of strategy and the strategic impact of operational capabilities linked to the development of flexible processes.

1.2 RESEARCH QUESTIONS

Initially, the scope of research was limited to the hot rolling operation. A review of existing research [17, 18, 23, 43, 85, 86] suggested that advanced scheduling methods were required in order to improve production flow in hot rolling. Focus was on the development of a simulation-based production scheduling system which could potentially streamline production by allowing mill planners to foresee and avoid problems¹.

¹ A similar system has been presented by Appelqvist and Lehtonen [2].

However, it soon became clear that the congestion and extensive buffering that occurred between process steps was a result of the design of current process technology as well as operational practice. The need for complex scheduling methods was a symptom of other problems, which should be targeted directly. It was concluded that a more fruitful approach would be to find and eliminate the cause instead of focusing on the symptom (scheduling).

After some time, the following research question was formulated:

RQ0: "How can steel producers combine a strategy based on a diverse highly value-added product mix with the need for continuously lowered production costs?"

This was broken down into three more specific questions:

RQ1: How should a method for analysis of the influence of product variety and process flexibility on production performance be designed?

RQ2: How do process flexibility influence performance when the degree of product variety is considered?

RQ3: How should the new methods and models be used to support the firm's strategy process?

1.3 CONTRIBUTION OF THESIS AND APPENDED PAPERS

Throughout the work on this thesis, there was an overarching idea that influenced the directions taken. However, the specific actions, experiments and analyses were the result of gradually arriving at new insights, where each was a logic consequence of the work that preceded that stage in the research process. The initial ambition of improving scheduling methods in hot rolling gradually evolved towards a search for understanding of how to improve steel production on a system level.

Over time different research activities were undertaken, probing into questions considered interesting at the time. Much time was spent analysing production data. Simulation models were implemented and a number of simulation experiments evaluated.

Some results were published on scientific conferences and in journals, but this thesis is not a summary of its appended papers.

These publications represent important steps in the research process since they gradually recognise the importance of product variety and process flexibility. However, the full picture is only communicated in this thesis.

The contributions of the different publications is summarised in the following.

PAPER I: Introduces dynamic process cost modelling (DPCM) and the five-step framework. Discusses process cost modelling and its role in the strategy process. Emphasises role of exploratory data analysis (EDA) in model testing and development. Case study illustrates use of framework to assess manufacturing capabilities and identify an improvement trajectory.

PAPER II: On hot charge operation of continuous casting (CC) and hot rolling mill (HRM), and how lean production methods can aid its implementation. Four hot charge modes were defined and related stages of mill integration: Cold charging—decoupled operation, hot charging—loose integration, direct hot charging—close integration and hot direct rolling—unbuffered operation. Improvement methods and steps in the integration processes were discussed.

PAPER III: Evaluates influence of HRM scheduling on performance in CC and HRM operations. First attempt at system dynamics (SD)-based production modelling. Model estimates charging temperature, work-in-process (WIP) and fraction setup time. Short scheduling periods and frequent schedule updates improved performance and reduced variations in WIP.

PAPER IV: Evaluates economic potential in improved process flexibility in HRM using a simple conceptual model. Identifies links between scheduling policies and poor process flexibility. Impact of setup time on cost of slab reheating, inventory and work-roll consumption.

PAPER V: Evaluates impact of improved process flexibility in HRM on inventory, energy and work roll costs using an improved model. Improved model replicates results from Paper iv. Elaborates on economic impact of work roll wear and work roll consumption.

PAPER VI: On links between steel producers' niche marketing strategies and product diversification. Discusses need for flexible steelmaking and continuous casting technology. Introduces concept of mould metallurgy for just-in-time steel production. Technical aspects on mould-metallurgy.

The structure of the thesis and main areas of contribution of the different publications is illustrated by Figure 1.

1.4 DISPOSITION

This thesis is about how strategic and operational capabilities should be identified and developed in order to obtain high performance and realise diversified low-cost production in steel plants. Three research questions target three areas of inquiry: method of assessment (RQ1), modelling and characterisation (RQ2), and implications for strategy formation (RQ3). Figure 1 illustrates the thesis' disposition and its relation to publications and research questions.

Chapter 1 (this introduction) motivates the research, sets goals and scope, and defines research questions. Appended papers are briefly summarised.

Steel production is described in Chapter 2.

Chapter 3 defines strategy and the strategy process. Implications of niche marketing strategies on product variety. The role of capabilities, strategy emergence, and the links to competitive frontiers and production innovation.

Chapter 4 introduces a dynamic process cost modelling (DPCM) framework. This framework and the relevance of modelling and simulation in organisational learning and strategy formation is discussed.

DPCM is applied on steel production in Chapter 5. Model design, causal loop diagrams (CLDs). Motivation for design, discussions of production features behind design decisions.

Chapter 6 presents a simulation analysis on the combined effect of product variety and process flexibility on plant performance and production cost based on models from Chapter 5. The chapter ends with a synthesis and discussion of the results.

The research results are concluded in Chapter 7. Research questions are discussed together and individually before some concluding remarks. The thesis ends with a critical review and suggestions for future research.

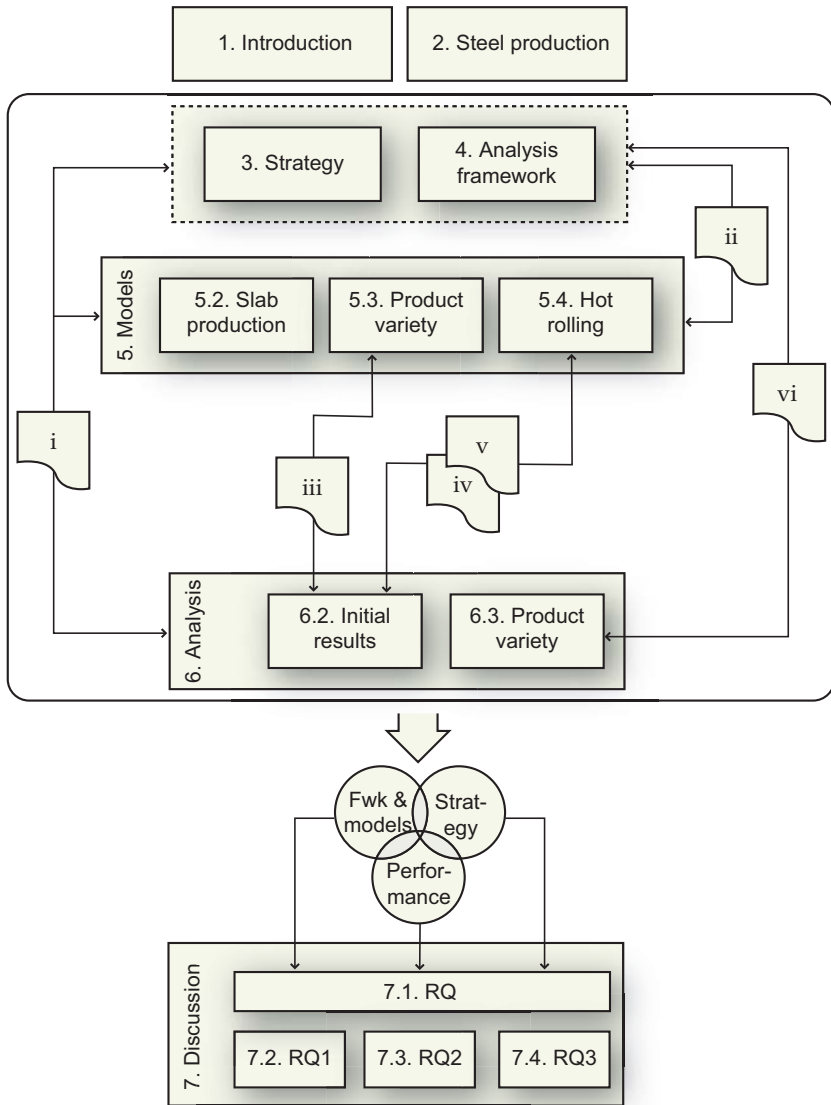


Figure 1: Thesis structure and main area of contribution of appended papers (i-vi). Research questions focus on analysis framework (RQ1), modelling and characterisation (RQ2), and strategy formation (RQ3).

STEEL PRODUCTION

2.1 PROCESS DESCRIPTION

2.1.1 *Overview*

Steel strip is typically produced through a combination of continuous casting and hot rolling. Integrated plants use blast furnaces to produce pig iron, which is combined with recycled steel scrap and virgin alloying materials in the steelmaking process. So-called mini-mills replace the blast furnace with electric melting furnaces and solely use recycled scrap and virgin alloys [8]. Steel making and hot rolling is often followed by pickling, annealing and cold rolling.

Outokumpu Stainless' Avesta works produces stainless steel strip in a typical mini-mill, shown schematically in Figure 2. A batch, or "heat", of carefully selected steel scrap is melted in the electric arc furnace (EAF). Alloying elements are added in the argon oxygen decarburisation (AOD) converter and the heat is further refined in the ladle furnace (LF) before it is cast in the continuous caster (CC) to flat rectangular workpieces ("slabs") of about 20 tonnes each.

Between the steel mill and the hot rolling mill (HRM) is a temporary storage, known as the slab yard, where slabs are kept in anticipation of being rolled to strip. Slabs are reheated before hot rolling. Hot rolled products can be sold directly to customers, but much is annealed, pickled and cold rolled to produce a shiny surface and further reduce thickness, sometimes down to as little as 0.1 mm.

Although steel production is often referred to as a process industry, it is in effect largely characterised by processing of batches. The intermediate product has different forms in different stages, e.g. a ladle of molten steel, a cast slab or a coil.

This thesis is mainly concerned with the link between CC and HRM. This part of production is shown schematically in Figure 3 and will be described further in the sections that follow. Steelmaking is also discussed briefly since it is intrinsically linked

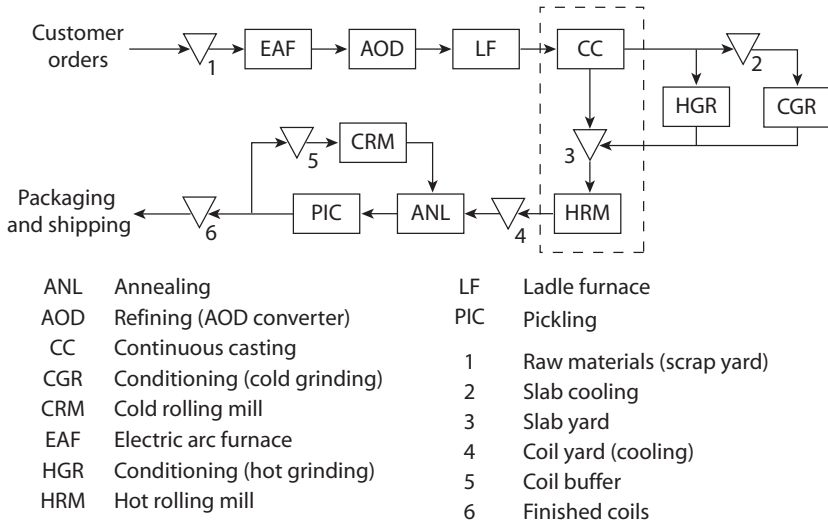


Figure 2: Schematic of a mini-mill for integrated stainless steel production. Numbers 1 to 6 indicate inventory buffers. The dashed frame indicates the thesis' context.

to the CC-process; the integrated meltshop/CC is sometimes referred to as steelmaking—continuous casting (SCC).

2.1.2 Steelmaking

Batches of steel scrap is melted in the EAF. The composition of scrap is chosen to roughly match that of the product with respect to major alloying elements like nickel and chromium.

The heat is then transferred to the AOD converter, where it is further refined with respect to content of carbon, chromium, nickel, molybdenum and other elements depending on grade. It is then moved to the LF for final adjustment of composition. The ladle LF also has an important role as a hot buffer between AOD and CC.

Batches in the meltshop are typically in the order of 100 tonnes. Partially filled batches are not produced since it reduces throughput and the efficiency of the refining process.

During continuous casting, molten steel is poured from the ladle into an intermediate container called the tundish. For a smooth casting operation, metal flow into the tundish must be

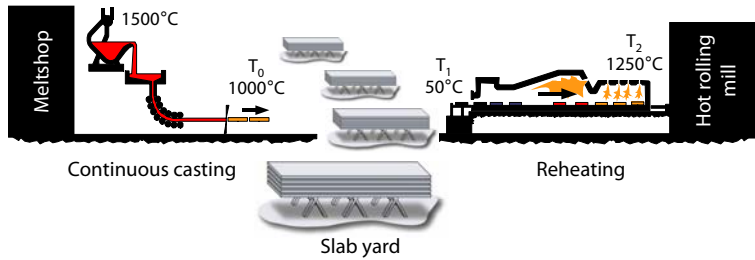


Figure 3: The link between continuous casting (CC) and hot rolling mill (HRM). Slabs are buffered in piles in the slab yard and reheated before entering HRM. Temperature immediately after casting, $T_0 \approx 1000^\circ\text{C}$. Charging temperature, T_1 , depends on cooling time but is often close to ambient temperature. Rolling temperature, $T_2 \approx 1250^\circ\text{C}$.

controlled such that the steel level remains constant. The steel enters a vertical water-cooled copper mould where a solid skin forms that contains the still molten metal in the centre. The shell is pulled from the mould into a series of cooling zones where water is sprayed onto the strand, ensuring a controlled solidification. The strand is then led out on a horizontal roller table where it is cut into slabs with a torch.

The casting rate varies for different slab geometries. In general a wider cross-section results in a slower cast. As a general estimate, it takes about 45 minutes to cast one charge. One 100 tonne charge then yields four or five slabs after casting.

When a slab has been cut, it is inspected for surface defects. If quality is acceptable, the slab is piled on a stack as seen in Figure 3. When the stack contains a few slabs, it is moved to the slab yard and the slabs are made available in the scheduling system of the HRM.

If the steel supply is interrupted during casting, the current cast has to be finished and a setup (turnover) of the caster carried out. The preceding melting and refining steps must therefore be well timed with the casting operation in order to ensure continuous operation.

If the steels of two consecutive batches are compatible [23], and the desired cross-section geometry is the same or within the limits of the casting machine's capacity for adjustment during operation, they can be cast sequentially without intermediate caster setup.

The average number of charges in one cast is given by the *sequence factor*. It is common practice to optimize the production schedule in order to minimise the number of setups and restarts in the casting machine, i.e. to maximize the sequence factor (see e.g. Tang et al. [85]).

If only effective processing time is considered, the complete melting, refining and casting of a charge and rolling of all slabs to coiled strip typically take less than five hours.

2.1.3 *Slab conditioning*

Stainless steels are less prone to oxide scale formation during processing than carbon steels. They are therefore more sensitive to surface defects than carbon steels, where defects can be removed with the oxide scale during the descaling operation in the rolling mill. It is often required that slab surfaces are corrected in stainless steel production. This is done in a slab grinding machine.

Slab grinding may be carried out in warm condition (hot grinding), or after cooling (cold grinding). Cold grinding requires slabs to be cooled down which adds to production lead times. The processing rate is higher in hot grinding since the steel surface is more workable when hot compared to when it is cold.

On-line quality control systems have been developed in the last decades, but these systems still have limitations. Defects are difficult to spot on a hot surface, and several stainless steel grades are still routinely cooled and inspected in cold condition. The difficulties associated with direct observation of defects has led to the development of computer aided quality control (CAQC) systems, see e.g. [19], which aim to detect the probability for defect formation through online observation of process parameters during casting.

2.1.4 *Hot rolling*

The rolling process is carried out at elevated temperature where the deformation resistance of the material is low. Slabs are therefore heated to about 1250°C in walking beam furnaces such as the one seen in Figure 4.

Modern reheating furnaces are equipped with control systems that regulate the power of the burners based on the current



Figure 4: Hot rolling at Outokumpu Stainless Avesta works. The roughing mill is located at the far left. Two walking-beam reheating furnaces are seen to the right.

conditions. The reheating process is controlled by models that predict the internal temperature of the slab as it travels through the furnace. Such models account for the material's thermal properties, slab geometry, heat content in the fuel, gas circulation and numerous other factors.

After reheating, the slab is rolled to strip in a number of passes. In the first step, thickness is reduced in 5 to 9 passes in a reversing roughing mill to form a transfer bar of about 25 mm height. The length of the transfer bar is typically in the order of 60 to 80 m.

The transfer bar then enters the finishing mill. Stainless steel mills are often equipped with reversing hot steckel mills like the one seen in Figure 5. Here, the strip is rolled to final thickness, typically between 2.5 and 12 mm. The strip temperature is in the range from 800 to 1250°C. Coil furnaces keep the strip temperature up to prevent excessive work hardening in the final passes.

Work rolls become worn during operation and must be replaced regularly. The most pronounced wear occurs in the contact



Figure 5: Steckel type hot strip finishing mill at Outokumpu Stainless Avesta works. Replacement roll pair is ready to be shifted in.

zone by the edges of the strip. In order to maximise work roll utilisation, rolling mill schedules are designed such that the width of strip progresses approximately from wide to narrow over the duration of a schedule.

As seen in Figure 5, replacement work rolls are prepared offline. During a setup the current work rolls are pulled out on a rail and the new pair is shifted in. The old work rolls are then conditioned in a roll grinding machine to remove surface defects that emerge during the rolling process. A pair of rolls typically last 30 to 60 grindings before they have to be scrapped, depending on the type of rolls.

The cycle times in the reheating furnaces depend on the power of the installed burners, but also on the reheating rate, geometry and initial temperature of the workpieces. Higher average charging temperature of slabs that enter the furnace means that less heating is required. The cycle time can be reduced which may

lead to reduced energy consumption depending on how the furnace utilisation develops¹.

The cycle time for the actual rolling operation follows from the rolled length and the rolling speed. This in turn depends on the number of passes and height reduction in each pass. Roll pass design must consider process parameters such as maximum reduction, roll force and drive torque, but may also have to consider the microstructural evolution in the material during processing.

2.2 STRATEGIC CONSIDERATIONS

According to a report from the Royal Swedish Academy of Engineering Science (IVA), all Swedish steel producers have chosen to compete through niche market (specialisation) strategies [39, p.58]. Establishment on a niche market may help the firm to avoid direct competition based on product cost. However, for most steel producers, cost remains an important competitive priority. This has important implications for manufacturing since the niche market strategy leads to increased product variety and small customer order volumes.

Manufacturing equipment and systems are strategic assets since they are based on large investments in time and money. Maslen and Platts [47] argue that the manufacturing equipment is the firm's most important asset and "a major determinant of competitiveness". Steel producers often upgrade manufacturing equipment, e.g. with improved control systems and measurement devices. The same rolling mill stands can be used for decades, which effectively means that the structure of production remains largely unchanged.

As discussed by Berry and Cooper [6], the choice of a niche market strategy (Section 3.3, p.21) may require changes in the existing manufacturing equipment to accommodate increasing product variety. This typically means adding flexibility to allow production to quickly shift to the product currently in demand (Section 3.6).

Plant organisation influences performance. A decentralised organisation with separate management of each process step may lead to an exaggerated focus on equipment utilisation. Utilisation

¹ Utilisation must be considered since it influences the efficiency of the reheating operation.

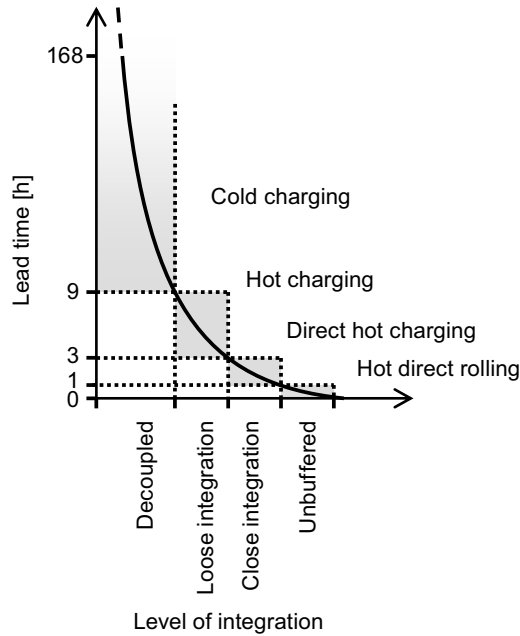


Figure 6: Levels of integration for different mill configurations, with corresponding hot charge mode and typical lead times from casting to rolling. From Paper ii [82].

can be increased through buffering, but high buffer levels may have a negative effect on the plant's overall performance. Such plants are likely to be forced to operate in decoupled mode with long leadtimes as illustrated by Figure 6.

Reduction of work-in-process (WIP) is central to improvement frameworks such as "lean production", but the structure of the manufacturing system may force production to operate with high levels of WIP. Meadowcroft [48] noted almost 25 years ago that "slab inventories in even well-managed plants can reach 10 to 20 days." This thesis argues that steel producers, particularly those who employ a niche marketing strategy, can improve the integration of process steps by increasing the level of process flexibility through strategic investments in equipment and operational practice.

STRATEGY

This chapter gives an overview of strategy and defines a frame of reference for the analysis framework presented in Chapter 4.

3.1 WHAT IS STRATEGY?

Strategy deals with long term planning and use of resources to reach set-up goals. It contains elements such as establishing purpose, setting direction, developing plans, taking major actions and securing competitive advantage [35].¹

However, strategic management is not a well defined field of research. Mintzberg et al. [50] recently identified ten different “schools”, where each has its own distinct view of what strategy is and is not.

In some respect, strategy targets everything a firm does to remain competitive in the market. Montgomery [53] states that “strategy doesn’t just position a firm in its external landscape; it defines what a firm will be.”

Strategy can be intentionally formulated by firm management, but much important work with strategic implications is a result of small incremental actions throughout the organisation. Also, while some intentional strategies are successfully realised, many remain unrealised. As a consequence, strategy is both deliberate and emergent, see Figure 7.

According to Tangen et al. [87], three strategic levels can be distinguished: corporate strategy, business strategy and functional strategy. Corporate strategy concerns selection of markets and localisation of key resources such as main offices, manufacturing and research units. Many companies are organised in business units that deploy their own business strategies to support the overarching corporate strategy and guide subordinate levels. Business strategies are broken down into functional strategies for

¹ The word “strategy” derives from the Greek word *strategós*, with the literal translation “army leader”, which is the title of the highest ranked military officer in the ancient Greek army.

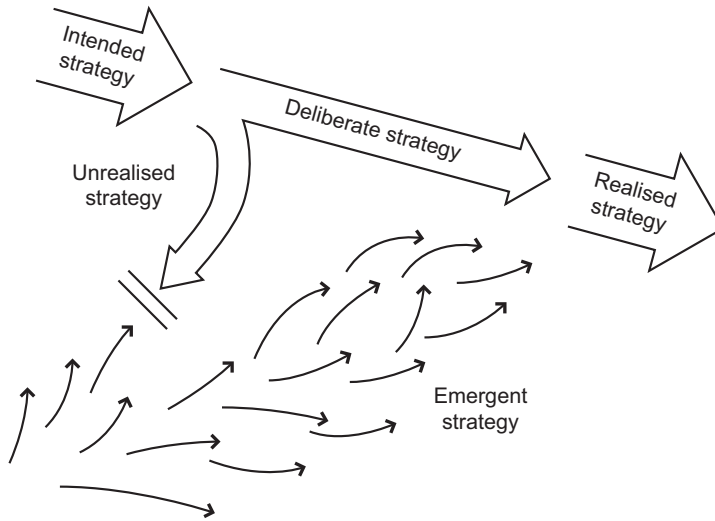


Figure 7: Realised strategy is a blend of deliberate and emergent strategies. Some intended strategies are never realised. From Mintzberg et al. [50].

marketing, research and development, finance, human resources and manufacturing.

Some general objectives of strategy can be identified [76]:

- Setting broad, long-term objectives, and planning a path towards an overall goal.
- Dealing with the total picture detached from, and above, the distractions of day-to-day activities.

Skinner [73, 74] recognised that manufacturing is central in corporate strategy. A search for new strategy models took off in the 1970's and 1980's when Japanese automotive manufacturers, with Toyota in particular, outperformed western brands on all dimensions of competitive performance [34, 96]. A number of new concepts emerged, e.g. the resource based view (RBV) [93], cumulative capabilities [26], and manufacturing and operational capabilities [34].

The top-down view on strategy with clearly distinct formulation and implementation phases is gradually being replaced by a more operational view (see Slack and Lewis [76]), where manufacturing strategy fits in naturally.

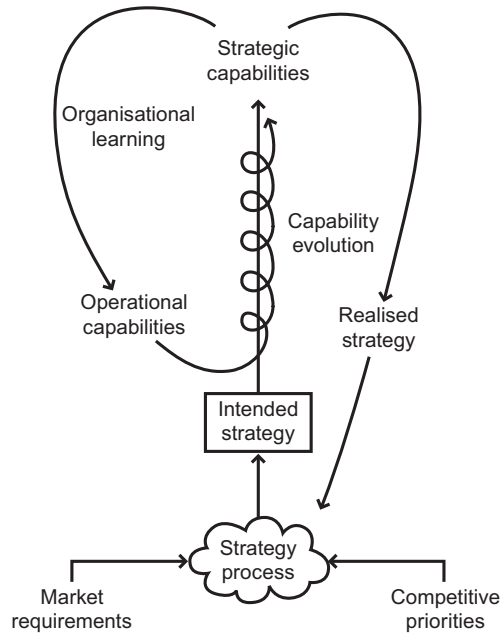


Figure 8: Illustration of how capabilities, organisational learning and capability evolution interact in strategy formation.

Figure 8 illustrates how a number of concepts that are discussed in this chapter fits into the view of strategy as intended and emergent on one hand, and as an evolutionary capability building process on the other.

3.2 THE STRATEGY PROCESS

A firm's official (intended) strategy is usually formulated in a more or less formal process known as the *strategy process* (Figure 8). The strategy process as taught at business schools has traditionally focused on economic planning and control. This approach has been heavily criticised [51, 13, 50] for neglecting the development of strategic capabilities and resources that form the basis for the firm's competitive advantage [93, 24].

Strategy, characterised as a "consistent pattern of decision" [35, p.27], has the objective of sustaining or enhancing the strategic capabilities of the organisation [34, 76, p.231]. Neglecting

to invest in new capabilities will most likely lead to declining competitiveness relative to competitors [13].

The predominant view of the strategy process [44] is that it consists of three separate steps which are performed sequentially:

- Formulation of functional strategy,
- implementation of the strategy, and
- development of operational capabilities.

A problem with this view is that it neglects emergent strategy. Realised strategy is therefore better understood as a blend of intended strategy and emergent strategy, which evolve together as suggested by Figure 8.

How strategies evolve as an individual and collective process, and what kind of solutions that are favoured, depend on the mental models that exist within the organisation [67]. According to Mintzberg et al. [50, p.178], “strategists are permanently trapped by bounded rationality ... and by their incomplete and imperfect perceptions of the ‘environment’”. They argue that the strategy process must recognise the importance of “insight, creativity and synthesis, the very things that the formalisation of planning discourages” (p.78).

According to Fujimoto [29], a firm’s improvement capability can be described in terms of routinised manufacturing capability, routinised learning capability and evolutionary learning capability. He argues that the evolutionary learning capability, characterised as “a certain dynamic capability for capability building, but it is not a routine itself”, allows one firm to outperform others by possessing better opportunistic learning capabilities [29].

Toyota developed TPS through what Fujimoto [29] calls “multi-path system emergence”. He argues that every-day problem solving “enhance the functionality of the system in a more or less routine manner” while multi-path system emergence is “a more ill-structured process, in which the system builder can predict and control the change process only partially” (p.90).

A recent account of how Ericsson AB came to get a leading position in IP technology attributes this to emergent strategy. It was, according to former CEO Sven-Christer Nilsson, “apparent that we had missed the IP-train. ... And now it turned out that we had IP-development in 15–16 places in the company. Most of this was probably unknown to the previous firm management.” [88].

The example illustrates that effective strategies evolve incrementally, evolutionary, and are only partially deliberate. Strategic capabilities evolve when existing organisational capabilities are leveraged to develop new strategic resources in innovative ways. This must be recognised in the strategy process in order to maintain a sustained dynamic fit between capabilities, market requirements and competitive priorities.

3.3 MARKET REQUIREMENTS

Mature industries like the steel industry are characterised by increased competition and price deflation due to overcapacity, in addition to a reduction in the number of firms. Under these circumstances companies seek to differentiate themselves from other firms [59]. Segmentation of a market allows each firm to focus on areas where it has its particular strengths [20].

The existence of an economic niche for a business depends on the existence of barriers to entry of competitors [90]. Such barriers include institutional or government arrangements that restrict entry or competition in an industry, natural barriers such as spatial distance and economies of scale, and barriers created by a business itself via product promotion and differentiation. Another type of barrier is to maintain an absolute cost difference, i.e. low cost production.

Niches can be created intentionally. Tisdell and Seidl [90] state that “three out of four generic competitive strategies recommended by Porter result in the creation of niche markets, namely the differentiation strategy, the cost focus strategy and the differentiation focus strategy.” Porter [62] defined four generic strategies (cost, differentiation, cost focus and differentiation focus) that aim to position the firm to avoid direct competition. However, markets are dynamic and “under imperfect competition, all firms occupy niches in the short term” [90]. To sustain a market position will require ongoing efforts to form and exploit niches that allow an above average firm profitability.

Firms that act on different markets will focus on different competitive priorities (cost, quality, dependability and flexibility [35, p.40]). Different prioritisations lead to identification of different strategic capabilities. Firms that compete in different niches must therefore develop different set of operational capabilities. This process is illustrated by Figure 8.

Steel producers typically differentiate themselves through quality and product flexibility. Market positions are based on research, e.g. within metallurgy and forming of high strength steels, stainless steels or tool steels, and focus on developing special (“value-added”) products with attractive properties.

Marketing strategies can be characterised as combined push/-pull, where “pull marketing” means that a market is identified first and a product is developed for it, while “push marketing” means that a product is developed first and a market is developed around it [59]. Hence, steel producers exploit potential gaps in the market, leading to product differentiation within their niche.

3.4 CAPABILITIES

Capabilities refer to a firm’s ability to “do something” in the sense to convert resources into action [16, 32]. They are cumulative and build on combinations of existing and new competencies and resources [26]. Development and strengthening of capabilities is at the core of the strategy process [34].

The terms “capabilities”, “strategic capabilities”, “manufacturing capabilities” and “operational capabilities”, all occur in the literature. These are examples of ordinary (“first order”) capabilities that express the ability of a firm “in equilibrium” to fulfil its competitive task [94].

In this thesis, the following definitions are used:

STRATEGIC CAPABILITIES High-level routines and resources that are recognised as strategically important in the firm’s intended strategy.

OPERATIONAL CAPABILITIES High-level routines and resources that are present in the firms operational functions.

DYNAMIC CAPABILITIES High-level routines and resources that are used by a firm to modify its existing operational capabilities.

According to this definition, a firm’s manufacturing capabilities are a subset of its operational capabilities.

“Dynamic capabilities” govern the rate of change of ordinary capabilities [94]. They allow an organisation to systematically generate and modify its operating routines in pursuit of improved effectiveness [97, 71].

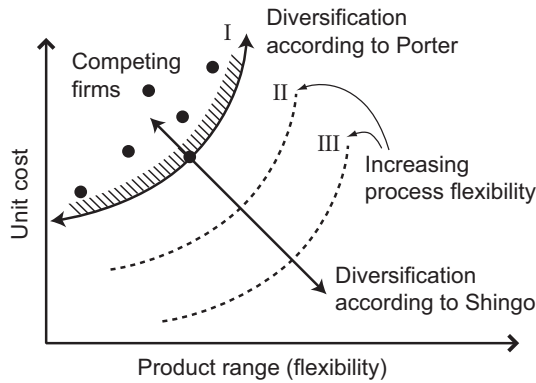


Figure 9: Competitive frontiers; Porter's generic strategy framework versus Shingo's SMED system.

Figure 9 illustrates the strategic role of operational capabilities. The figure shows a competitive frontier [33, 34, 21] or "efficient frontier" [76], which defines the performance limit for existing production technology and methods.

High variety and bulk steel producers belong to different strategic groups and are not direct competitors according to Porter's framework [62]. They are positioned differently along the x-axis of Figure 9. If the current frontier (I) is assumed to be static, the strategic task is to position the firm such that it finds a niche within its segment, typically either as a low cost/low variety producer, or as high cost/high variety producer.

However, competitive frontiers are not static. Firms that develop new and innovative operational capabilities can open-up new frontiers. This changes the competitive situation in an industry and illustrates how strategic capabilities follow from operational capabilities. From this perspective, the strategic value of Shingo's SMED-system [70] can be understood. SMED provides a systematic method for improvement of process flexibility through setup time reduction. Instead of the traditional trade-off between low cost/low product variety versus high cost/high product variety, Shingo is in fact offering a systematic method to drive the competitive frontier towards diversified low-cost production. Shingo developed SMED for Toyota, but as the same ideas are applicable in steel production.

Realisation of diversified low cost steel production requires that the long-term development of operational capabilities puts

the firm in a position to reach new frontiers. Poor understanding of cause and effect may lead plants onto learning trajectories that inadvertently destroys performance [66]. The effects may be long lasting since “once a dominant design or standard has emerged, the costs of switching become prohibitive, so the equilibrium is self reinforcing” [77, p.350].

The trade-off of product variety versus process flexibility is fundamental for production system design, e.g. concerning the location of the customer order decoupling point and production control strategies as discussed in the next section.

3.5 PRODUCTION CONTROL

The order coupling policy (Section 3.5.1) and the control mode (Section 3.5.2) determine to a large extent the operational characteristics of production. However, which type of system that can be realised is much dependent on product variety and flexibility requirements as discussed in the following.

3.5.1 *Order coupling policy*

The customer order decoupling point (CODP) or “order penetration point” [69, 58, 65, 57] provides a way to define production typology that is more precise than the traditional “mass”, “batch” or “continuous” production terminology [65]. Four operational modes can be used to characterise production [65]:

1. make-to-stock (MTS);
2. make-to-order (MTO);
3. assemble to order (ATO); and
4. engineer to order (ETO).

Figure 10 applies these concepts on two steel plants that operate in decoupled and integrated mode respectively (see Figure 6). Production in meltshop/CC and HRM can be either MTS or MTO. Strict MTS places the CODP at the slab yard. All slab variants (grade/geometry) must then be stocked. In contrast, strict MTO requires that slab production is strictly customer order driven, eliminating the need for a slab yard.

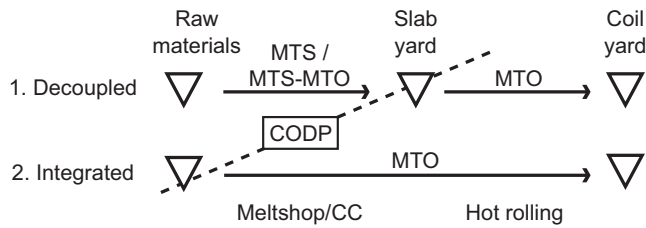


Figure 10: Location of customer order decoupling point (CODP) and related order coupling policies for (1) decoupled, and (2) integrated, meltshop/CC and HRM.

ATO is not applicable to steel production. An ETO system can be conceived e.g. if a custom steel variant is developed based on the requirements of an individual customer.

Denton et al. [22] report how steel plants are moving from MTO towards hybrid make-to-stock/make-to-order (MTS-MTO) due to increasing product variety and a desire to differentiate by improved customer service e.g. by offering short and consistent order fulfilment times. This development comes at the price of increased inventory. Different optimisation techniques can be used to determine which products to keep in stock without incurring excessive costs [22, 40].

MTO is used for products with low turnover. However, customer orders for less than the minimum batch size in SCC yield surplus slabs that must be stocked in anticipation of future customer orders. Production is thus hybrid MTS-MTO even in the absence of a controlled inventory.

3.5.2 Control mode — “push” versus “pull”

The “push” and “pull” control modes concern how production orders are released into production. Push systems schedule the release of work based on demand, while pull systems authorises the release of work based on system status [37, p.340].

Pull-based systems implement control systems that ensure that production orders cannot be released if WIP exceeds a given limit, known as a “WIP-cap” [38]. Hence, there is an upper limit on the amount of WIP that is allowed in the system. How the WIP-cap is implemented is not crucial. Pull production is possible in e.g. kanban, CONWIP and MRPII systems [38].

Without a WIP-cap, production operates in push mode. This is typical for the steel plant described in Chapter 2: Production in meltshop/CC continues as long as there are jobs to be processed, regardless of the state in the next step. Similarly, production in HRM continues as long as there are jobs to be processed without consideration of the state in the receiving end.

Control mode and order coupling policy are related, but there is no direct link between e.g. MTO and pull production. As discussed above, meltshop/CC use combined MTS-MTO due to the existence of excess slabs, while HRM produce to customer order (MTO). But there is no WIP-cap and both meltshop/CC and HRM operate in push mode: Both use a production schedule spanning e.g. one week, and each works on in its own pace without consideration of system state in downstream operations.

The feasible lower limit for a WIP-cap and the potential to operate in pull mode is reduced if:

- The minimum batch size exceeds the minimum order volume; and
- there is high product variety in upstream operations.

This is illustrated by the following example.

The box-and-whisker plot² in Figure 11 summarises residence times in the slab yard for more than 4000 slabs that were cast and hot rolled in a stainless steel strip plant. The sample contained 164 combinations of steel grade and slab width, arranged in five groups, a–e, after declining order frequency.

75% of all slabs in group (a) were rolled within ten days with a median of five days. For the other groups the median is from 10 to 18 days, and the third quartile is from two weeks to a month. There is an apparently linear relation between customer order frequency and mean residence time.

The conclusion is that mean transfer time for slabs (and hence WIP) is determined by product variety. High variety steel production with decoupled meltshop/CC and HRM is a push production system. The potential to reduce WIP is limited unless production can be made more flexible and capable of delivering right-sized batches for low-volume products.

² A box-and-whisker plot [91, p.39] is a graphical representation of a 5-number summary. The box centres around the median and extends from first to third quartile. Whiskers extend from the box to the inner fences located at 1.5 times the extension of the box. Values outside the whiskers are treated as outliers.

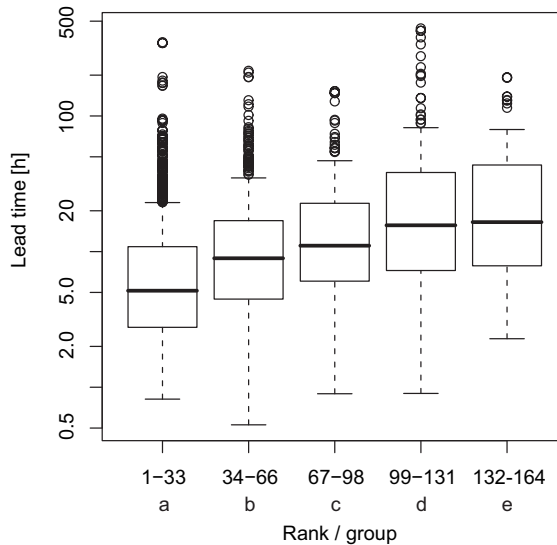


Figure 11: Box and whisker plot showing lead times for five product groups. Products were ranked after order frequency and the total number of observations split equal among groups. Lead time decreases with increasing order frequency.

3.6 FLEXIBILITY

Capabilities that follow from flexibility on the machine and plant levels become more important when the plant is producing a wide product range and production volumes are low for each variant [4]. In that case setup costs tend to increase.

Flexibility is a characteristic of the interface between a system and its environment that “functions as an absorber for uncertainty” [21]. It has a buffering function, e.g. volume flexibility that allows production to adapt to variations in order rate.

Process flexibility yields the capability to process an arbitrary sequence of products with minimum time and cost penalty. It provides the ability to change quickly among a group of known products [92, 11], and to move quickly, smoothly and cheaply from one state to another without great cost and/or organisational disruption [75].

Hence, flexibility serves as a “buffer against variability” [38] by increasing the short-term ability to process an unplanned sequence or combination of products.

The degree of process flexibility depends on both available technology, the policies that guide its operation, and the organisational capabilities to realise the desired policies. The SMED system [70] provides a systematic method to increase process flexibility in production.

In the context of steel production, process flexibility determines (at any given time) the capability

- of the meltshop to produce a particular steel grade;
- of the continuous caster to cast a particular steel grade and slab geometry; and
- of the hot strip mill to roll a slab of a particular grade, width and thickness into the desired target thickness.

Steel producers can choose to implement different technologies depending on product variety and flexibility requirements. Continuous casting is less flexible than ingot casting: Ingot casting may sometimes be preferred for a plant that produces a large number of low-volume grades. Hot boxes or heat pits can be used to reduce heat losses by slowing down cooling of newly cast workpieces.

3.7 SUMMARY

Strategy must acknowledge that change follows from a blend of intended and emergent action. Production and operations strategy must maintain a dynamic fit between production capabilities, market requirements and competitive priorities.

Performance improvement in the case of high product variety requires alignment of the pursued marketing and manufacturing strategies [6]. A firm cannot successfully enter a market if the required operational capabilities are unavailable. New investments must therefore be evaluated with respect to operational capability requirements following from any chosen strategy.

Chapter 4 presents a framework that is designed to support organisational learning through development of dynamic process based cost models. This framework is later applied to assess the influence of product variety in steel plants.

METHODOLOGICAL FRAMEWORK

This chapter introduces a framework for evaluation of the strategic value of operational capabilities in production. The framework is based on DPCM, a system dynamics (SD)–based approach to process cost modelling.

The strategic value of model based analysis and learning is discussed in Section 4.1. Some aspects on simulation as an experimental method are covered in Section 4.2. This is followed by an overview of process cost modelling principles in Section 4.3. Finally, Section 4.4 elaborates on how the framework can be used in capability assessment.

4.1 MODEL BASED STRATEGY SUPPORT

4.1.1 *The capability gap*

Chapter 3 concluded that formulation of a successful strategy requires in–depth knowledge of internal operative capabilities and industry–specific requirements of the market in which the firm competes. Further, strategy formulation does not primarily rely on detailed analysis and control, although such tools are valuable for assessment of the feasibility of a proposed plan after it has been conceived. This view stresses the importance of cultivating an environment where strategically important ideas for production improvement can emerge and turn into realised strategy.

Mintzberg and Westley [52] argues that rational decision making, which progresses through a clearly defined process of problem identification, diagnosis, solution design followed by decision, has limited real–world applicability. In contrast, real decision making often follows a pattern of “groping followed by sudden sharp insights that lead to crystallisation” ([52, p.90]). They describe this process as one of preparation, incubation, illumination and verification.

Improving organisational learning in areas that are thought to be strategically important can therefore be expected to increase

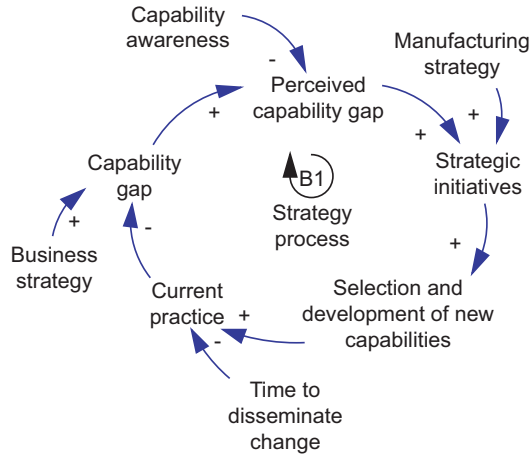


Figure 12: The author's view of the strategy process.

the number of cross fertilisations where old and new knowledge is combined into new and improved competitive capabilities.

Figure 12 shows how the author of this thesis interprets the strategy process. Central to this model is the existence of a *capability gap*. Additionally, the model introduces a distinction between the actual, effective capability gap (which cannot be objectively measured), and the perceived capability gap¹.

In order to reduce the effective capability gap, it is necessary to make the right improvements with respect to the business environment and current capabilities. This requires that the organisation's perception of the capability gap matches the effective capability gap reasonably well such that accumulated improvement initiatives converge towards a desirable improvement trajectory.

The discrepancy between the effective and perceived capability gaps is determined by the level of capability awareness, defined in Paper i [79] as "the level of insight, based on the available knowledge, tacit or formal, that guides firm management's perception of the gap between current practice and the capabilities that are required to successfully realise the chosen business strategy".

¹ Based on the assumptions of bounded rationality. Cf. third paragraph in Section 3.2, p.19.

Improving the level of capability awareness amounts to improving the mental models of how production can handle its current environment in the most efficient way. As noted by Sinreich et al. [72], the knowledge gained by a model which describes the “correct” system performance is essential for the detection of errors and faulty system performance.

Implementation of change takes time, but may eventually disseminate throughout the organisation and become the new current practice. The effective capability gap can thereby be reduced, leading to better fulfilment of the requirements of the business strategy.

4.1.2 *Improving capability awareness*

Production systems tend to display so-called system-of-systems behaviour (Bjerkemyr [7]), meaning that they are characterised by complex behaviour due to a blend of evolutionary development, self-organisation, heterogeneity, emergent behaviour and complex networks. Traditional systems engineering approaches appear to be insufficient to fully understand the resulting dynamics, and the individual’s inability to conceptualise such systems greatly affects the process of engineering [7].

Hence, the relations between product range, production capabilities, productivity and production cost are complex and emergent and notoriously hard to define.

For a model to be intuitively accessible and still useful for technology adoption decisions, it should go beyond the limited detail of existing economic models but apply a more aggregate perspective than most engineering models (Field et al. [27]). Such models provide causal explanations for how certain types of investments will influence performance.

The explanatory power of a model is of equal importance as its ability to produce correct predictions. This limits the types of models that are useful for improving organisational learning since the causal relations must be explicit. This is characteristic for so-called white-box models.

White-box modelling makes the causal structure and relations between the resources that yield a capability explicit and improves understanding of how system behaviour emerges. System dynamics (SD) based approaches to promote organisational learning and improve the quality of strategy decisions have been

proposed by e.g. Lyneis [46], Wolstenholme [95] and Gary et al. [31]). In contrast, so called black-box modelling can produce correct predictions, but the model does not contribute to understanding of the underlying phenomena [49].

The proposed methodological framework is based on white-box modelling using SD-based dynamic process cost modelling (DPCM). Production system models form the core of these cost models.

When applied, the framework yields two types of results:

- A causal structure and a set of relations between entities in the model that constitute a “theory” of how capabilities in production emerge and are employed.
- Model characteristics, based on simulation output, that promote understanding of how configuration is related to performance.

Both model development and results analysis can help to develop an intuitive understanding of effective capability requirements, including the effect of product variety. This process is referred to as improvement of capability awareness (Paper i [79]).

4.1.3 *The five-step framework*

This section presents a framework for dynamic process cost modelling (DPCM) that was proposed in Paper i [79].

The five-step framework consists of five steps (Figure 13), which are carried out iteratively until the model reaches an acceptable level of maturity:

1. Problem identification. The problem structure is established and relevant processes, operations and cost elements identified.
2. Process modelling. Manufacturing processes are modelled with an emphasis on technology. Models are validated, e.g. through discussions with domain experts, comparison with experimental or in-process data, or comparison with reference models.
3. Operations modelling. Materials and information flows are introduced to link individual processes. Buffers are

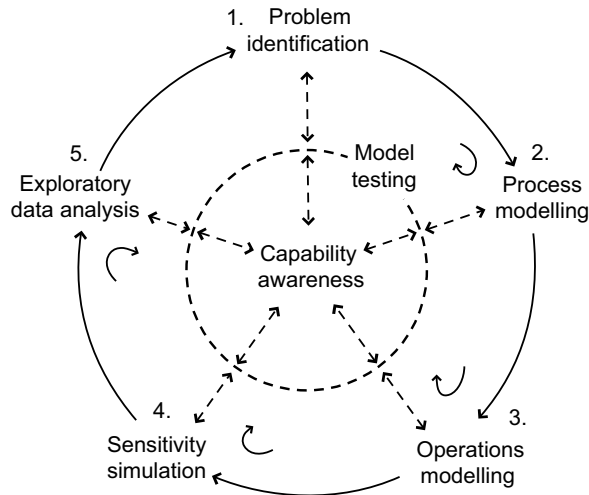


Figure 13: The five-step framework. From Paper i [79].

modelled as levels. Some decision processes may involve discrete event modelling.

4. Sensitivity simulation. The model is exposed to Monte-Carlo simulation with different ranges and combinations of input, which captures the characteristics of the model and often reveals inconsistencies that are otherwise hard to detect.
5. Exploratory data analysis². Linked data plots are used to find patterns and anomalies in the sensitivity results. This typically leads to the formulation of new hypotheses that serve as input to the problem identification stage of the next iteration.

The framework emphasises continuous testing of models, which is particularly important in situations where historical data is unavailable or difficult to obtain [78]. Validation is not a separate activity. Rather, as seen in Figure 13, which emphasises the iterative nature of the framework, it is integrated in all steps of the framework.

A central idea is that new insights often lead to a revised problem statement, which changes the direction of model deve-

² See Section 4.4.2, p.39.

lopment. This may occur e.g. when a cost element that initially was thought to be important turns out to be small in relation to another cost element that was excluded at first.

4.2 SIMULATION

The dynamic process cost modelling (DPCM) approach used in the five-step framework relies on system dynamics (SD), which is a form of continuous simulation. This section provides a background by discussing the nature of simulation models (Section 4.2.1), simulation methodologies including SD (Section 4.2.2) and model testing (Section 4.2.3).

4.2.1 *Nature of simulation models*

An industrial operation, or any other system, can be represented by a model. Different types of models exist. Shannon [68] defined a topology where models can be scale, schematic, analogue and mathematical representations of reality. Law and Kelton [41] identify models as either physical or mathematical. Mental models refer to our subjective internal representations of a system (Senge [67]). Common for all is that a model is a simplified representation of reality designed to capture some aspect of the behaviour of the original system.

Some simulation models are based on causal inference between entities in the model. Such a model can be claimed to embody a theory about the modelled system. However, as any theory, a simulation model can at best produce a more or less accurate prediction of the behaviour of the real system. Popper [61, p.42] writes that theories “should not be mistaken for a complete representation of the real world in all its aspects; not even if they are highly successful; not even if they appear to yield excellent approximations to reality.”

Simulation models are mathematical in a different sense than analytical models, e.g. a linear program [64], where the problem must be cast into a particular overall structure to be mathematically tractable. The overall behaviour of a mathematical simulation model arises from the interaction of its parts. The state of the simulated system is given by the collection of parameters and variables that are needed to describe it at a particular time relative to the objective of the study [41].

Simulation analysis is experimental in the sense that a model is supplied with a set of initial conditions and executed. The researcher is able to make changes to the model and study the result. Careful experimental planning is often necessary since execution of a model can be time consuming. On the other hand, some models execute quickly, facilitating the generation of response surfaces that comprise the results of hundreds or even thousands of simulation runs with different input configurations.

4.2.2 *Simulation paradigms*

Mathematical simulation models may be further divided into *continuous* or *discrete event* simulation models.

Discrete event (DE) simulation models are frequently used in production modelling. According to Sweetser [84], DE simulations often have a strong empirical basis because they usually model concrete, observable processes. The modelling of the system evolves over time by a representation in which the state variables change instantaneously at separate points in time [41]. These changes of state are defined as events, and the state of the model remains constant between events.

System dynamics (SD) is a continuous modelling and simulation methodology that is primarily used in strategy development, analysis of policy options, and analysis of dynamic processes where capturing information flow and feedback are important considerations. It facilitates a high level of abstraction, focusing on problem structure, causal links and feedback between variables [84]. As for other types of continuous simulation, the model consists of differential equations that give relationships for the rates of change of the state variables over time [41].

SD, originally termed Industrial Dynamics by Forrester [28], was primarily developed for analysis of industrial supply chains. It has since been used extensively to analyse the dynamics of business systems as well as social systems, e.g. by Senge [67] and Sterman [77].

Policy analysis or modelling of social systems often require incorporation of “fuzzy” qualitative aspects of behaviour that can be difficult to quantify but nevertheless important for the performance of a system. As a consequence model testing is less focused on validation against historical data and puts more

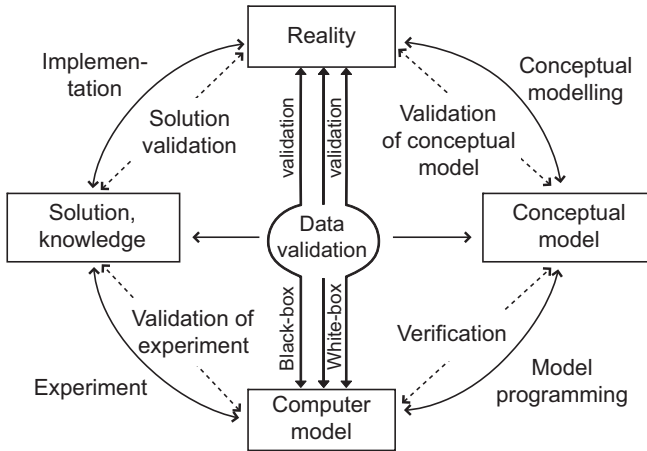


Figure 14: Steps in the simulation process. Adapted from Brooks et al. [9]

focus on interaction with domain experts in order to capture and improve system understanding [84].

4.2.3 Model testing

Model validation concerns whether the model assumptions constitute a proper representation of the studied system. A related concept is model verification, which concerns the proper implementation of these assumptions as a simulation model.

A general simulation modelling process is iterative as illustrated by Figure 14 (based on Brooks et al. [9]). There is a distinction between white-box validation and black-box validation. White-box validation focus on the internal design of the model. The model's logical and theoretical foundation is evaluated to ensure that the model assumptions are sound.

Black-box validation compares simulation output with real-world data, e.g. simulated processing times with statistical distributions from a production database. If no empirical data is available, triangulation with results from a different simulation model can be attempted.

Representation of causal structures is central for SD-models. It is thus not sufficient to ensure output validity since “‘validity’

means validity of the internal structure of the model, not its output behaviour" [3].

System dynamics literature emphasise continuous model testing against all sorts of available data. Inclusion of qualitative (unmeasured) data is advocated by Sterman [78] since "omitting structures or variables known to be important because numerical data are unavailable is actually less scientific and less accurate than using your best judgement to estimate their values". Forrester [28, p.57] argues that "to omit such variables is equivalent to saying they have zero effect — probably the only value that is known to be wrong!"

Sweetser [84] suggested that SD modellers are more comfortable with introducing "best guesses" and expert opinions into their models than are discrete event simulation (DES) modellers. As Sterman [78] notes, in those cases that empirical data is missing for variables that were suggested to be important during the modelling process: "Frequently, it is because no one thought these concepts were important." In SD modelling, the importance of a variable is typically determined by how well it fits into the causal structure of the model.

In short, validation should be seen as a process of learning, not merely as a process of finding errors.

4.3 PROCESS COST MODELLING

Section 4.1 introduced process cost modelling in support of the strategy process, a concept that is elaborated in Paper i [79].

A three layered approach to cost modelling is proposed by Field et al. [27], based on

1. a *process model*, where fundamental engineering principles are used to assess how the necessary resources for production can be employed;
2. an *operations model*, in which the physical implementation of the manufacturing processes as well as the organisation of resources is considered. It is suggested that the operations model contains a dynamic aspect since it helps the manufacturer to "optimise its use of one resource that is most difficult to obtain — time" [27];
3. a *financial model*, in which resource requirements are converted to economic costs.

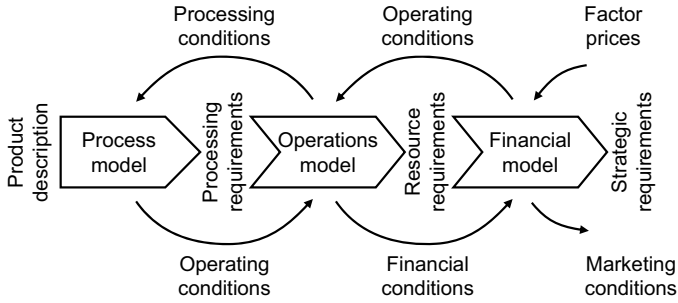


Figure 15: A three layered approach to cost modelling with separate process, operational and financial layers. Elaborated from Field et al. [27].

The separation of performance into process, operations and financial models makes it possible to undertake a wide range of strategic analyses of technological opportunities [27]. Physical resources and cost have been separated as far as possible in the models presented in this thesis; most cost estimations are based on projected resource consumption.

Figure 15 illustrates the distinction and interaction between the three layers during operation. The layered structure permits that one layer is changed independently from the others, which is useful e.g. for assessment of existing manufacturing technology under varying operating conditions.

4.4 CAPABILITY ASSESSMENT

This section discusses why cost models are useful tools for capability assessment (Section 4.4.1), why an exploratory approach to data analysis is advocated (Section 4.4.2), and how DPCM are combined with EDA in the capability assessment procedure (Section 4.4.3).

4.4.1 Use of process-based cost models

A proposition in this thesis is that the development and use of process-based cost models will yield a deeper understanding of the causal structures between production capabilities and performance. This brings input to the strategy process by improving

capability awareness, thereby reducing the gap between the effective and the perceived capability gap (Figure 12).

Some evidence that is obtained from this procedure is:

- A causal structure embodied in the causal loop diagram (CLD).
- Quantitative relations of causation embodied in the model equations.
- Transient dynamic behaviour of the model.
- Steady state dynamic behaviour of the model.

Strategic considerations by definition concern the behaviour with respect to varying and unknown future environmental conditions. Decision variables must be quantified and available as configuration parameters in the model. Additionally, it must be possible to account for varying product range since this is linked to the choice of business model and market positioning.

Cost-based performance metrics are easy to communicate and a primary consideration for managers when investments are assessed. However, cost-based performance metrics can be problematic. Price fluctuations influence performance even though physical resource consumption is unaffected. As a consequence, financial performance appears to vary although resource productivity is unchanged. It is therefore important to remember that cost reflects the consumption of resources. It is the mechanisms behind resource consumption that must be addressed in order to improve performance.

Different aggregate measures can also be conceived, e.g. a weighted sum of scores for performance with respect to generic capabilities. See Cleveland et al. [14] for an example.

4.4.2 *Exploratory approach*

The SD-based approach on which the proposed five-step framework is based reveals the causal structures that link capabilities to performance. However, the complexity of production systems models means that numerical simulation is often necessary in order to understand how different parts of a model interact.

Experimental planning reduces the set of open questions, keeps down the number of simulation runs and reduces the size of

the output dataset. Still, researchers must frequently screen vast amounts of output data for which finding relevant patterns requires substantial effort.

EDA is primarily directed towards searching for interesting but not immediately obvious model behaviour. Visual qualitative analysis plays an important role in this process. The usefulness of an exploratory approach to data analysis was stressed by Tukey [91, p.3] who claimed that “unless exploratory data analysis uncovers indications ... there is likely to be nothing for confirmatory data analysis to consider.”

The data analysis phase consists of two clearly separated activities [91]:

- Exploration, dominated by a search for interesting data and indicators.
- Evaluation, with the aim of attributing meaning to the evidence found.

A main purpose of EDA is learning. The visual and qualitative analysis helps the analyst to uncover quantitative indicators of system behaviour using graphical tools and specialised data-visualisation software. The use of linked data plots will allow the analyst to interact interactively with the data, which can greatly speed up the learning process.

4.4.3 *Capability requirements analysis*

This section illustrates the use of interactive EDA in the search for a viable improvement trajectory. A production model is subjected to a sensitivity simulation in order to produce a response surface [41]. The numerical output is then stored in a database, which is imported into a computer software that supports linked views [15]. Effectively this produces a linked database which can be explored visually and interactively by the analyst.

Interactive plotting, brushing and shading in dynamic linked scatterplots [15] are the key steps operations in the following analysis [79]. Figure 16 shows the principles for how this is done. The steps in this procedure are:

1. Painting of goal regions.
2. Evaluation of performance indicators for the defined goals.

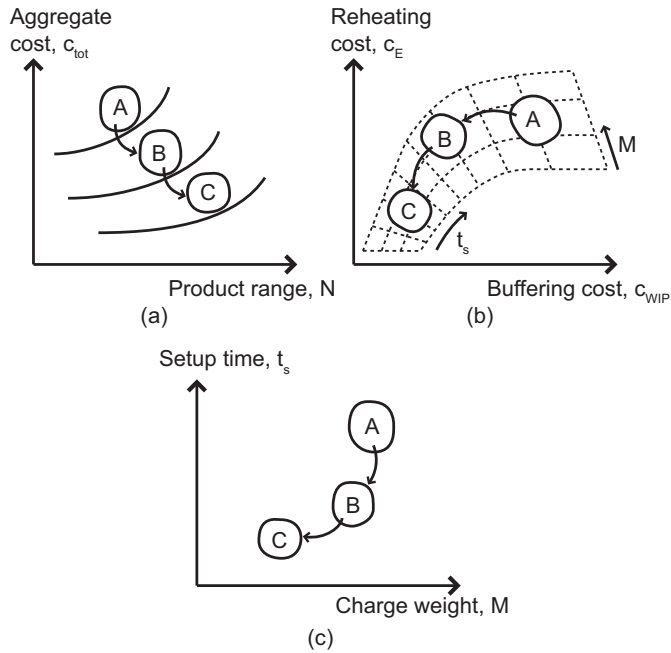


Figure 16: Steps in the capability requirements analysis. Adapted from Paper i [79].

3. Linking of performance indicators to configuration parameters.

The strategic goals are defined and brushed in the linked database as seen in Figure 16a. Each goal corresponds to the opening-up of a new competitive frontier as illustrated by Figure 9 (p.23).

A pair of performance indicators are plotted in a second view (Figure 16b). This view represents another projection of the response surface onto the plane spanned by the chosen variables, e.g. reheating cost and buffering cost. The performance indicators will map onto the new projection and the painted regions appear with distinct colour or symbol.

It may be possible to infer directly how the projection of the performance indicators in Figure 16b depends on configuration parameters, e.g. setup time and charge weight, if the dependencies are apparent. However, it can be helpful to open up a third view that shows the desired configuration parameters. If all data

points except those representing the goal regions are hidden, the mapping of these (painted) regions in the design space will show.

4.5 COMMENTS

Chapter 3 argued that development of strategic capabilities to support the firm's market strategy and choice of competitive priorities is a central strategic issue. Since strategic capabilities are derived from operational capabilities, identification of the "right" operational capabilities becomes crucial.

The method outlined in this chapter is concerned with how capability requirements are analysed and made explicit. The aim has been to present a method that helps analysts and strategy makers to develop and communicate an intuitive understanding of how production performance is linked to operational capabilities. As previously discussed, the method must support evaluation of process flexibility requirements due to product variety.

A central concept is the notion of a capability gap — in particular the gap between the objective capability gap and the capability gap as perceived by the organisation. In this chapter it was argued that model based learning through development and application of white-box production models is particularly useful for this purpose.

The next chapter applies the proposed framework and presents a comprehensive dynamic process cost model for the steel production system outlined in Chapter 2.

MODELLING STEEL PRODUCTION

The capability requirements analysis method described in Chapter 4 uses dynamic process cost modelling (DPCM) to assess the economic impact of changes in production processes and operational policies. This chapter presents how the steel production system was modelled.

Figure 17 shows the modelled system schematically. Melts-hop/CC and hot rolling mill are decoupled by the slab yard, and each unit organises its own production scheduling¹. The existence of multiple scheduling points indicates that production is operating according to “push” principles [45, p.45].²

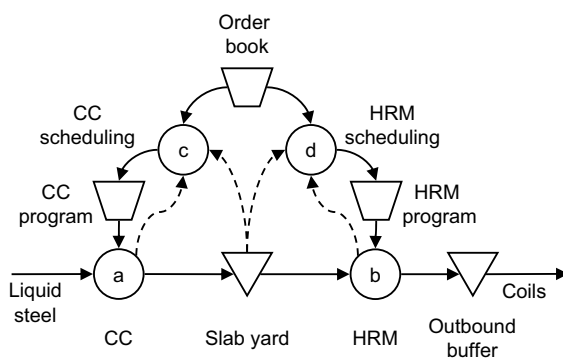


Figure 17: Continuous casting and hot rolling mills with decentralised production scheduling functions. From Paper ii [82].

The rest of this chapter is structured as follows.

An overview of the model is found in Section 5.1.

Section 5.2 presents models for slab production and order processing: Production control (Section 5.2.1), caster operation and scheduling (Section 5.2.2), WIP-control (Section 5.2.3), order processing (Section 5.2.4) and the market (Section 5.2.5).

¹ Scheduling is coordinated by a central staff-function, but meltshop/CC and HRM are scheduled individually by logistics staff subordinate to the respective mill manager.

² See Section 3.5.2, p.25.

Section 5.3 presents some models for the impact of product variety: Definition of product groups (Section 5.3.1), estimation of the amount of setup time depending on product range (Section 5.3.2) and estimation of the amount of ordered material per charge of produced steel (Section 5.3.3).

Section 5.4 presents models for slab reheating and hot rolling: HRM scheduling (Section 5.4.1), reheating furnace operation (Section 5.4.2), heat losses during cooling (Section 5.4.3), and work roll wear and roll changes (Section 5.4.5).

5.1 MODEL STRUCTURE

The model was structured according to the three-layer principle discussed in Chapter 4.3. This is seen in Figure 18. The model is partitioned into four main areas: continuous casting, slab yard, reheating and hot rolling.

Parallel product flows were used to model product variety. Four product groups were defined, where each group represents a group of product variants with similar customer demand rate and properties.

The order coupling policy and the control mode (push/pull) are major determinants of model behaviour.³ A customer order backlog is used to hold orders-in-process. Order forecasting is used to estimate an expected customer order rate from historical data.

Figure 18 compiles the major parts of the model, but it does not describe how they interact. What appears to be a simple sequential flow is in fact more complex.

The upstream part of the model, including slab production and production control, is seen in the policy structure diagram in Figure 19. The downstream part of the model, with slab reheating and hot rolling, is seen in another policy structure diagram in Figure 33, p.62.⁴

³ See Sections 3.5.1 and 3.5.2.

⁴ A policy structure diagram [77, p.710] shows the high level stock and flow structure of the model without all the detail present in a causal loop diagram. Rounded rectangles denote organisational subunits, policies or decision rules and show the boundary of organisational units.

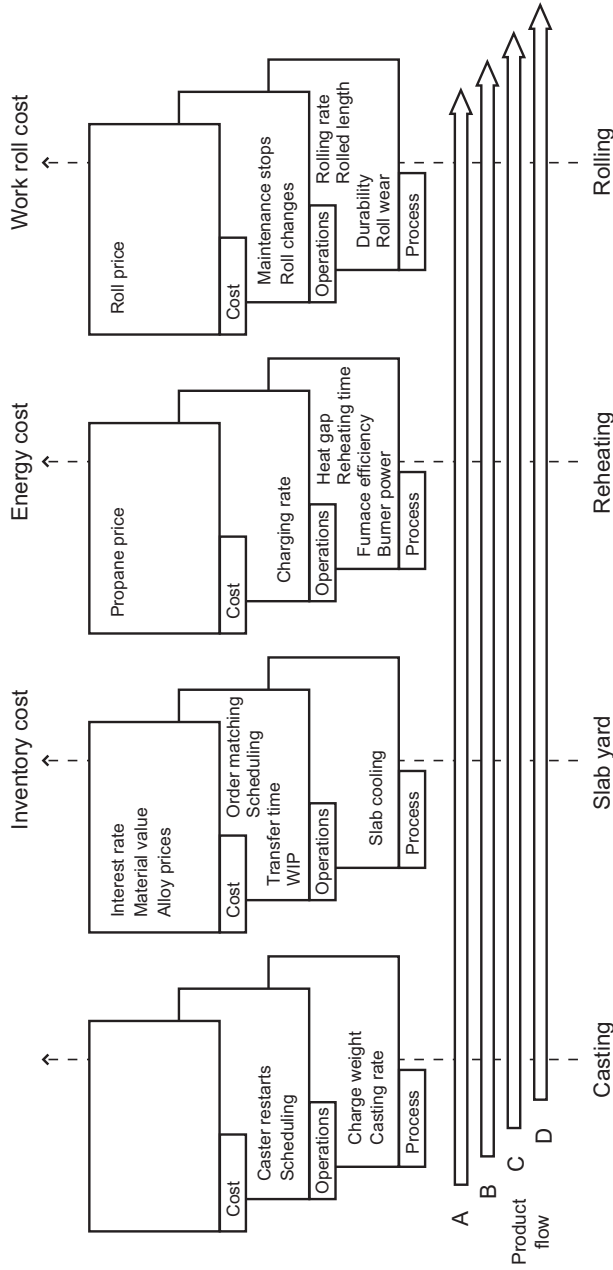


Figure 18: Model topology. Four parallel product flows are simulated. Content of the process, operations and financial layers is shown. From Paper i [79].

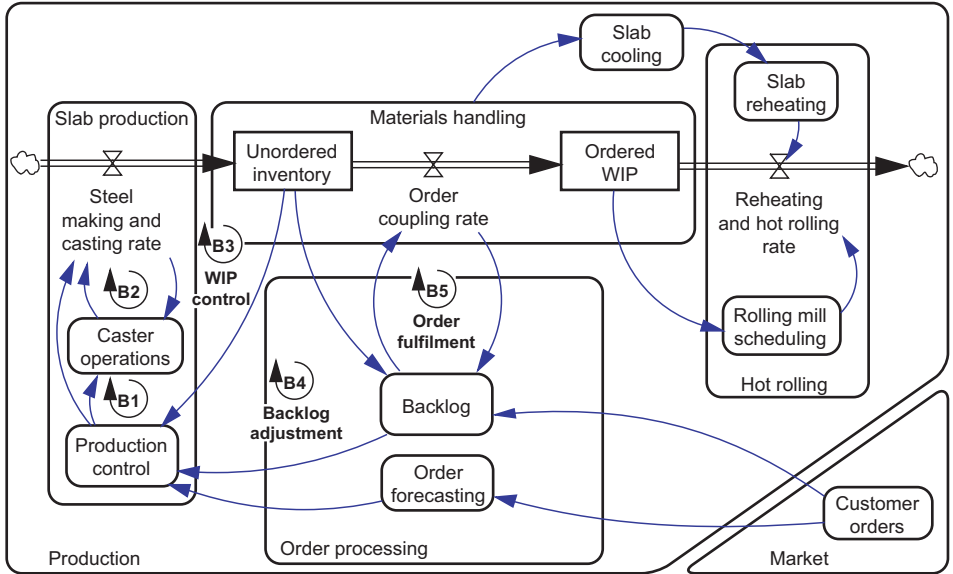


Figure 19: Policy structure diagram for the production model.

5.2 SLAB PRODUCTION AND ORDER PROCESSING

This section discusses the five balancing loops B1, B2, B3, B4 and B5 seen in Figure 19. These loops represent the left hand side of Figure 19.

5.2.1 The production control loop

The production control loop (Figure 19, B1) handles short term adjustment of the “steel making and casting rate”. The CLD for loop B1 is seen in Figure 20. The “desired mean casting rate” is adjusted for each product group to match its “desired mean production start rate”. The production start rate is in turn balanced by the WIP control loop (B3) and the backlog adjustment loop (B4). The time constant for the change rate, “desired casting rate adjustment time”, was set to 24 h.

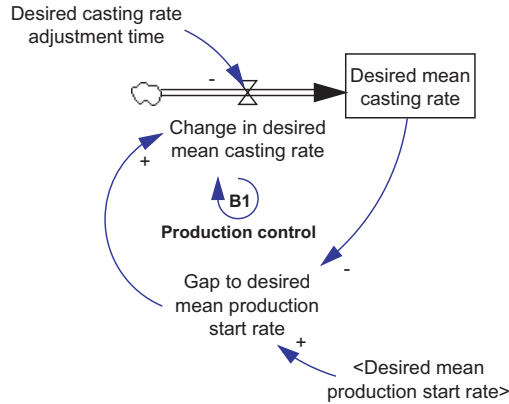


Figure 20: The CC production control loop (B1) handles the pacing of meltshop/CC. The desired casting rate is adjusted against the desired production start rate.

5.2.2 The caster operation and scheduling loops

The caster operations loop, Figure 19 (B2), consists of two sub-loops (B2a) and (B2b) seen in Figure 21. The caster operations loop (B2a) controls the effective casting rate with respect to demand and capacity constraints. The schedule levelling loop (B2b) controls the order in which product groups are processed and adjusts schedule fractions.

The effective casting rate is limited by the “max effective casting rate”, which is calculated with respect to caster turnovers and the nominal maximum plant specific casting rate.

Production in meltshop/CC is scheduled in programs with a fixed number of charges per program. The time span needed to complete a program is defined as the scheduling period, T_p . The effective scheduling period depends on the effective casting rate and the fraction of setup. Calculation of the scheduling period requires estimation of the fraction setup, which is expressed by the sequence factor.⁵

The schedule levelling loop (B2b) distributes production time between product groups. It also levels the casting rate between groups by adjustment of the schedule fraction for each group according to the flowchart in Figure 22. Product groups are

⁵ A model for estimation of the sequence factor is described in Section 5.3.2.

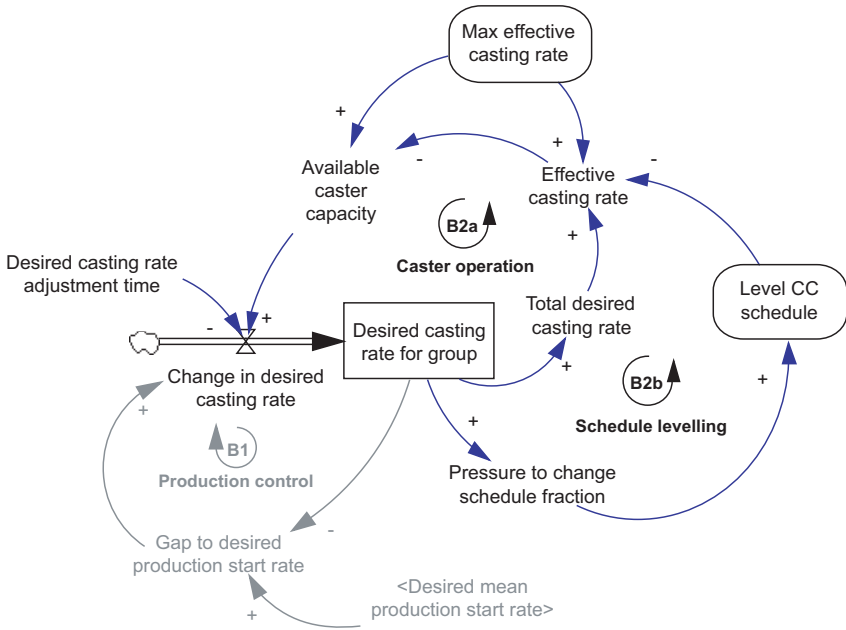


Figure 21: The CC operations loop (B2) consists of two sub-loops. The caster operations loop (B2a) controls the effective casting rate with respect to demand and capacity constraints. The schedule levelling loop (B2b) controls the order in which product groups are processed and adjusts schedule fractions.

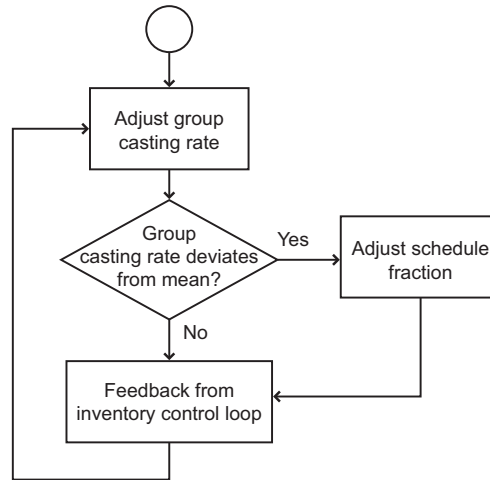


Figure 22: Principle for adjustment of schedule fraction within the production control model.

processed in a predetermined sequence based on order frequency and slab width in the following order:

1. wide high-volume products (A),
2. wide low-volume products (D),
3. narrow high-volume products (B), and
4. narrow low-volume products (C).

The background to these scheduling policies is discussed in Paper iv [81] and Section 5.3, 54.⁶

The schedule fraction is the fraction of the total scheduling period, T_p , that is allocated to the production of each group. The levelling principle is illustrated by Figure 23 where (a) shows how the desired casting rate, which is governed by the production control loop (Figure 20), varies between groups. After levelling, (b), the casting rate is equal for all groups. The schedule fraction of each has then changed such that the integral of the production rate $r = r_i(t)$ is constant before and after levelling for each group, $i \in \{A, D, B, C\}$.

⁶ The scheduling model and the implementation of product groups is based on subscripted variables and vector functions. These features are described in Chapter 17 of the Vensim User's Guide: <http://www.vensim.com/documentation/vensim.htm>

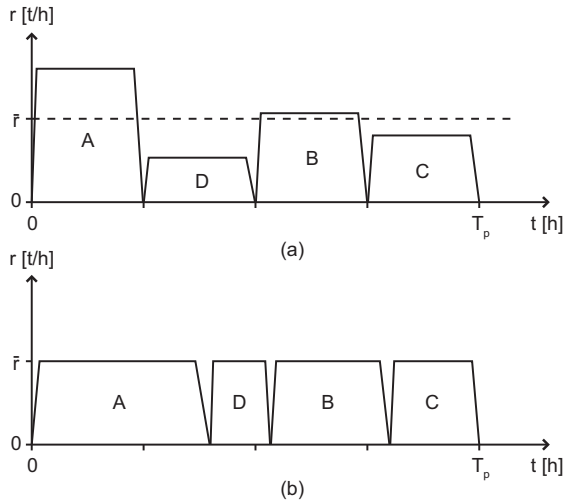


Figure 23: Levelling of casting rate between product groups by adjustment of the schedule fraction for each group: (a) Each group has a schedule fraction of $1/4$, but the casting rate varies between groups. (b) The casting rate has been levelled but the schedule fraction varies between groups.

Levelling the production rate in the model by adjustment of the schedule fraction corresponds to real-world scheduling and pacing of production in meltshop/CC.

5.2.3 The WIP control loop

Production of slabs is initiated when an existing customer order cannot be served with inventory slabs. This mechanism is found in Figure 17, which shows a feedback loop from the slab yard to production scheduling (c). This structure is also found in Figure 19: The WIP control loop (B3) uses information from the slab yard (“unordered slabs”) to adjust the “production start rate” which controls the caster operation.

The CLD in Figure 24 shows the detailed structure of the WIP control loop (B3). Increasing in-process inventory (“unordered slabs”) for any particular product group will lower the “desired mean production start rate” (Figure 24) for that group.

All flows represent aggregated values for each product groups as discussed in Section 5.3.1, p.54. Individual slabs, coils or

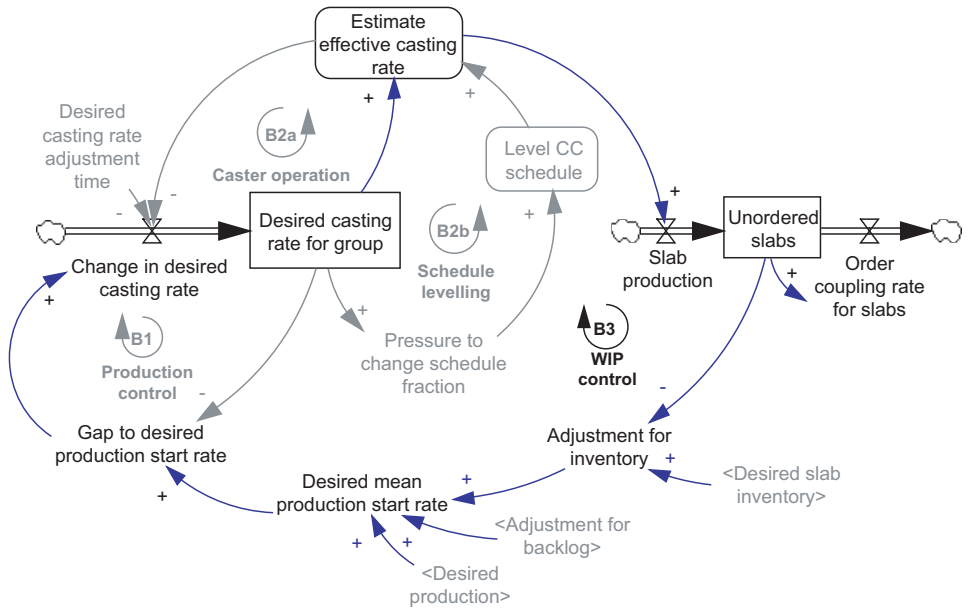


Figure 24: The WIP control loop (B3).

other intermediate products are not represented in the model. Hence, an increased level of unordered wide low-volume slabs will cause a reduction of the production start rate for the group as a whole.

5.2.4 The backlog adjustment and order fulfilment loops

The order processing model seen in Figure 19 contains two loops: The backlog adjustment loop (B4) and the order fulfilment loop (B5).

Figure 25 shows the structure of the backlog adjustment loop (B4). This loop adjusts the desired production start rate based on the difference between the estimated (forecast) and actual order backlog.

Without the backlog adjustment loop, a low order forecast will lead to shortage of unordered slabs. Likewise, overestimating demand will yield excess inventory. It is the task of the backlog adjustment loop to compensate for deviations between forecast and actual demand.

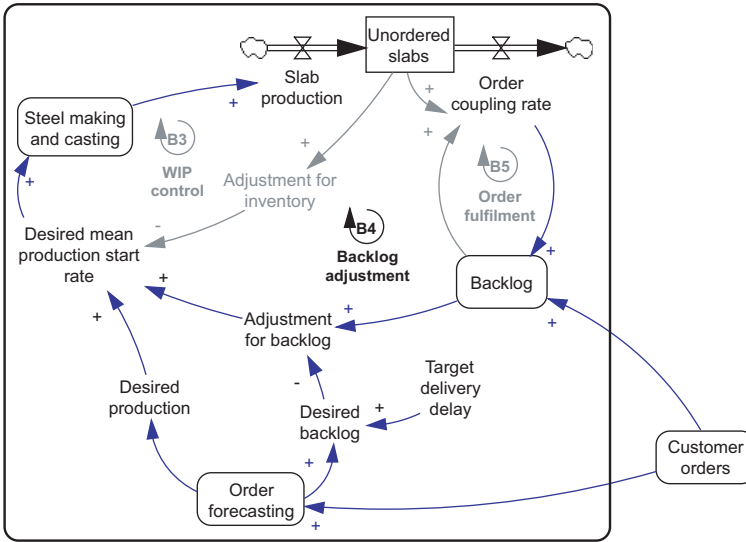


Figure 25: The backlog adjustment loop (B4) adjusts the desired production start rate to compensate for differences between order forecast and actual order rate.

A “desired backlog” is calculated based on the expected order rate and the desired order fulfilment time (“target delivery delay”). “Adjustment for backlog” is the difference between actual backlog and desired backlog based on forecast. A positive adjustment increases the desired production start rate, while it is decreased by a negative adjustment.

Figure 25 also shows the order fulfilment loop (B5). The structure of the order fulfilment loop is seen in more detail in Figure 26. This loop links customer orders to unordered slabs and releases production orders to the hot strip mill.

The hot strip mill operates according to an MTO policy (Section 3.5.1): A production order is issued only when a customer order exists. Figure 26 shows how orders in the backlog are released and linked to physical slabs. Every time this happens, the backlog is decremented correspondingly.

The “order coupling rate” is the rate with which orders in backlog are linked to physical slabs. Orders are released and linked to available slabs such that the target delivery delay is met as long as the stock of unordered slabs is not depleted.

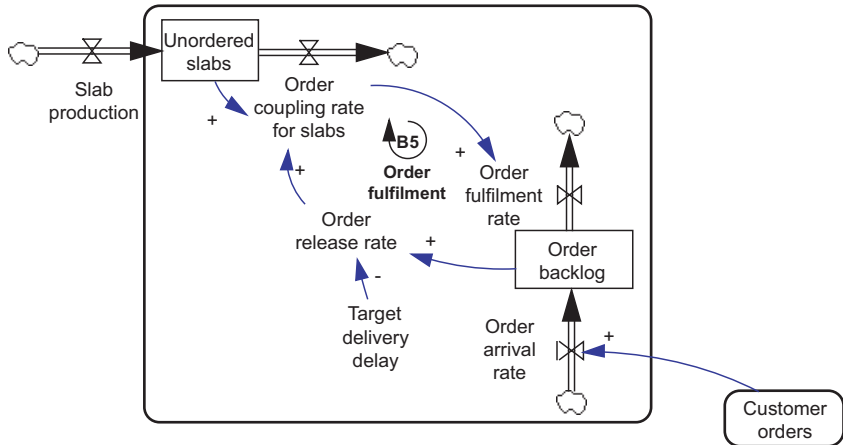


Figure 26: The order fulfilment loop (B5) issues production orders for hot rolling and links customer orders in backlog to slabs. The target delivery delay is met as long as slabs are available.

The availability of unordered slabs varies over time and between product groups. If the order rate is equal for two product groups, the inventory level is still likely to differ between these groups. Slabs with low turnover rate can remain in stock for a long time⁷. Empirical data has showed that 10% of the product variants often represents 50% of the production volume⁸. The turnover of such products is high and all slabs from a particular charge are normally hot rolled within ten days (see Figure 11, p. 27).

5.2.5 Customer orders

As seen in previous sections, production is controlled by a combination of forecast and actual customer demand. Forecasts are based on historical data and adapt gradually to changes in customer order rate. The used model is based on first order exponential smoothing as described by Sterman [77, p.716]. Its structure is seen in Figure 27.

The customer order rate can be given in at least three ways:

⁷ Discussed in Paper ii [82]. The lead time from casting to hot rolling for slabs cast in sequence during one week varied from one day to more than ten weeks.

⁸ Discussed in Paper vi [5] and Paper i [79].

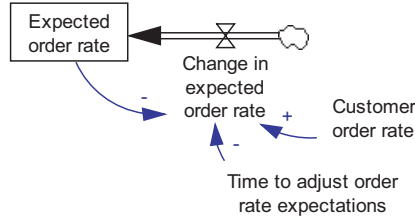


Figure 27: Order forecasting.

1. A model parameter with a pre-set value that can be varied as part of the experimental procedure.
2. An estimated (intrinsic) parameter used to simulate performance when demand and capacity are in equilibrium.
3. A variable that is computed by a function or sub-model that is used to approximate real variations in demand.

The model implements the second approach and adjusts the order rate such that production is approximately in equilibrium over the long run. The sensitivity simulations presented in Chapter 6 are based on the assumption that the plant is operating with stable demand at 90% of its estimated capacity.

5.3 MODELLING PRODUCT VARIETY

This section discusses the modelling of product variety. Section 5.3.1 gives a background to the definition of product groups. Section 5.3.2 presents a model for estimation of the sequence factor based on product variety. Section 5.3.3 presents another model, which estimates the fraction of ordered material per charge depending on customer order rate and batch size.

5.3.1 *Product groups*

System dynamics is a continuous simulation method, so production is expressed as rates with respect to the chosen unit of time. Seeing production as an aggregate flow is often intuitive. In practice, order rates are often expressed in (t/month) as in Figure ???. Models in this thesis express time in (h) and production rates in (t/h).

Order frequencies for different product variants vary widely in special or stainless steel production. This is seen in the variation in lead time for slabs shown in Figure 11 (p.27) and in Paper ii [82].

Tesfamariam [89, p.111] discusses modelling of multiple products through introduction of “pseudo composite products”. In gear manufacturing, gear models with similar properties can be aggregated into a pseudo-composite “gear”, which represents the group as a whole. Paper i [79] showed that the same approach can be used in steel production.

Figure 28, which shows production data from a steel plant during a period from January 1 to January 31 2006, will be used to illustrate the choice of product groups.

The upper part of Figure 28 shows width and thickness for slabs that were cast during the period. Time of casting is indicated on the x-axis. The lower part shows the leadtime from CC to HRM for slabs that were assigned to a HRM program that spanned from Thursday January 26 to Sunday January 29.

A line is drawn from each leadtime data point to the inclined axis on the right hand side of the plot. This inclined axis shows the position of each slab in the HRM schedule. The time axis of this scale is magnified compared to the main x-axis.

Each data point in the lower half of the plot is linked to a corresponding point in the upper half. It is thereby possible to obtain the slab thickness, slab width, leadtime to rolling and position in the HRM schedule for each slab.

From Figure 28 clusters with similar slab properties and lead-times can be identified. These clusters have been indicated as A, B, C and D. Each group is distinguished by order frequency (high/low) and by slab width (wide/narrow). Groups A and D contains wide slabs, while groups B and C contains narrow slabs.

The positions of the different groups in the schedule, i.e. the order in which slabs are processed in the rolling mill, result in a so-called coffin shape. It is found that the order in which slabs have been scheduled for rolling is such that wide slabs are processed in the beginning of a HRM schedule, while narrow slabs are rolled at the end of the schedule. This corresponds to standard scheduling practice which is conceived to maximise work roll utilisation.⁹

⁹ Discussions of HRM schedule design policies are found in Papers iii [80] and iv [81].

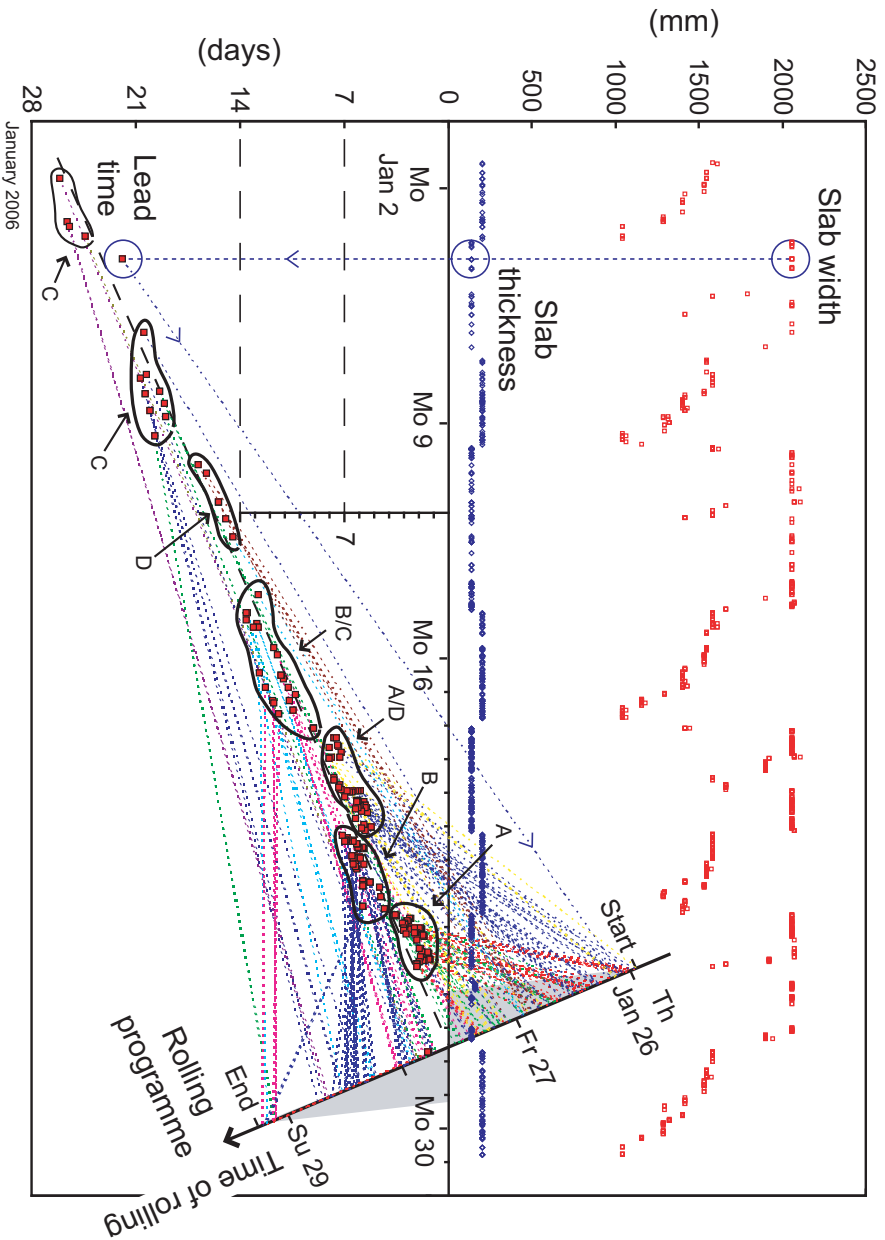


Figure 28: A hot rolling mill (HRM) program plotted together with one month's production in the continuous caster (CC). The inclined axis shows a magnified view of the HRM program. The lower part of the plot shows the leadtime for each slab in the HRM program. The upper part shows production in CC with thickness and width for each slab. Four product groups can be identified.

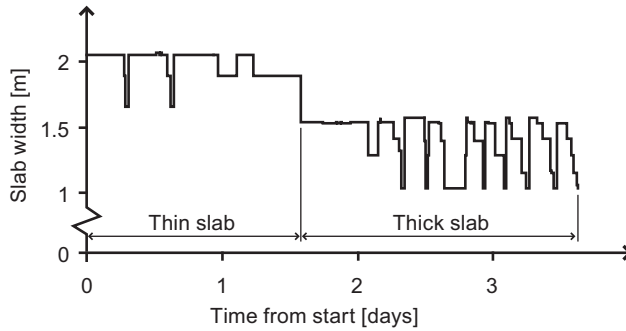


Figure 29: Distribution of slab widths over the progress of a production schedule in meltshop/CC.

This pattern is also seen in Figure 29: Wide slabs are cast in the beginning of the program while narrow slabs are cast in the end.

According to Buzacott and Callahan [10] (cited in [63]), the optimum scheduling policy for hot rolling mill charging from soaking pits is to never charge cold ingots when hot are available. This principle is applied in the model. High-volume products are thus always scheduled first as reflected by the scheduling policies listed in Section 5.2.2, p.49.

5.3.2 Fraction setup

The sequence factor is a measure of the mean number of charges that can be cast in sequence without an intermediate caster turnover (setup). The effective production capacity cannot be determined unless the amount of setup time is known. In an aggregate analysis, where production is represented by rates, an average sequence factor (and fraction setup) can be estimated.

The number of charges that are processed in sequence between setups can vary significantly. Several charges can be cast in sequence for steel grades with high turnover, while one charge at a time is produced for grades with lower turnover.

No published model for the relation between product variety and the fraction of setup was found in the literature. The model proposed in this section assumes that the following is known:

- The fraction of high and low volume variants relative to the total number of variants (range fraction).
- The fraction of high and low volume variants relative to the total production volume (volume fraction).

Figure 30 shows the structure of the sequence factor model. It consists of three loops: The “production cycle” loop (R1), the “compatible grades” loop (R2) and the “schedule fragmentation” loop (R3). These are described below.

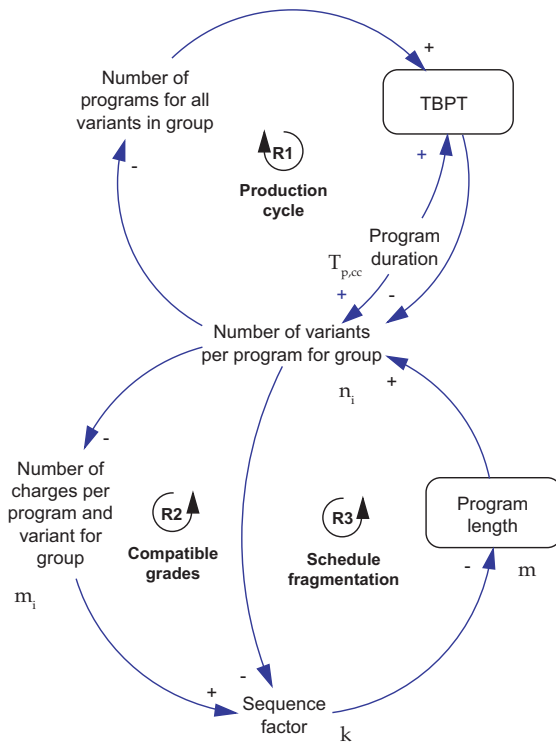


Figure 30: The sequence factor model consists of four loops: The “production cycle” loop (R1), the “time between production times” loop (B1), the “compatible grades” loop (R2) and the “schedule fragmentation” loop (R3).

The number of programs needed to produce all variants in a product group is estimated by the “production cycle” loop (R1). Each group contains a given number of product variants. It is assumed that production follows a rolling schedule, and a

specific time between production times (TBPT) can be defined for each product group. The task of loop R1 is to determine TBPT, which defines a production cycle for each group such that each variant in the group is produced exactly once before the production cycle starts over.

The number of variants in a group that is scheduled for each program, n_i , is the fraction of the program duration to the duration of the production cycle (TBPT) for each group:

$$n_i = \frac{T_{p,cc}}{TBPT} \min [N_i, m]. \quad (5.1)$$

Here, N_i is the total number of variants in the group and $T_{p,cc}$ is the program duration, or scheduling period (see Figure 31).

The “compatible grades” loop (R2) determines the number of charges per variant that can be cast in sequence. It is assumed that all charges are cast in sequence for each variant that is scheduled for the present program. Caster turnovers are carried out each time the processing of a variant has been completed.

Further, it is assumed that the number of charges per program for a group is the product of the group’s volume fraction and the total number of charges per program. The number of charges reserved for *the group* is then split equal between all variants in the group that are scheduled for the current program. This is the purpose of the “schedule fragmentation” loop (R3), which reduces the sequence length when the product range increases.

The mean number of charges between setups, i.e. the sequence factor, k , is thus given by

$$k = \frac{\sum n_i m_i}{\sum n_i}, \quad (5.2)$$

where n_i is the “number of variants per program” (Figure 30) for group i , and m_i is the “number of charges per program and variant” for that group.

5.3.3 Fraction ordered material

Depending on the charge weight (batch size) in the meltshop, there may be less ordered material at production time than the minimum batch size. The expected effect of reduced charge weights is that some of this overproduction is eliminated. This is controlled by the submodel for estimation of the fraction of ordered material per charge.

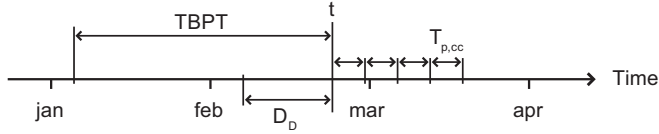


Figure 31: Key concepts for estimation of customer order fraction per charge. Time between production times (TBPT), target delivery delay (D_D) and CC scheduling period $T_{p,cc}$.

Figure 31 shows some key concepts used in this model. The time between production times (TBPT) is the time needed to produce all product variants. For low volume variants, this is typically the effective processing time needed to produce one charge of each variant. The target delivery delay, D_D , is the time needed to process the entire order backlog for a model in equilibrium. Large values of D_D can improve performance but may be unacceptable from a customer service perspective.

The following equations are incorporated in CLD seen in Figure 32. The amount of ordered material per product group in order backlog is given by the product $r_{x,i} \cdot D_D$ where $r_{x,i}$ is the customer order rate for the group. The ordered quantity per charge, $M_{x,i}$, becomes

$$M_{x,i} = \frac{r_{x,i} D_D}{N_i m_i}, \tag{5.3}$$

where N_i the number of variants for group i . The fraction ordered material per charge is then

$$x_{M,i} = M_{x,i}/M, \tag{5.4}$$

where M is the charge weight.

The total production capacity is distributed over the total number of product variants. If the number of variants increase, the produced volume per variant decreases while the total production volume is unchanged.

5.4 SLAB REHEATING AND HOT ROLLING

This section discusses the four balancing loops B6, B7, B8 and B9, seen in Figure 33.

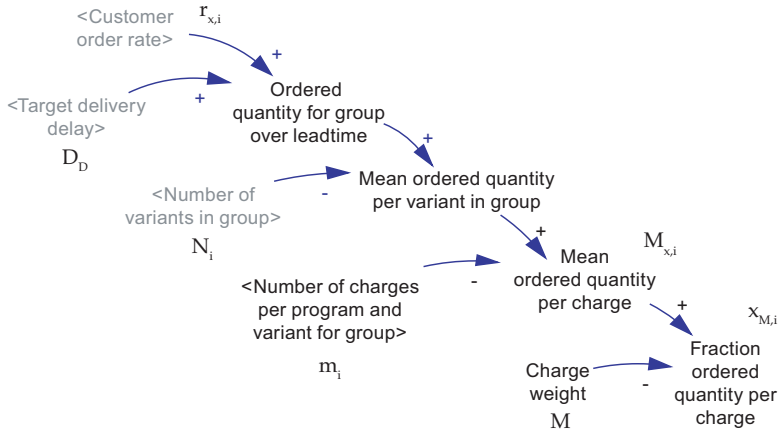


Figure 32: Model for estimation of the fraction of ordered material per charge. The program duration and the number of charges per program and variant for each group are obtained from the sequence factor model (Figure 30).

The HRM scheduling model is based on the model used in Paper iii [80]. Models for slab cooling and reheating are discussed in Appendix A.

5.4.1 The scheduling operation loop

When slabs are assigned to customer orders in the order fulfilment loop (B5, see Figure 26) they receive the status of “ordered slabs” and are made available for scheduling in the hot strip mill. The scheduling operation loop (B6) pulls slabs from the “ordered WIP” buffer (Figure 19) into the “reheating buffer” seen in Figure 33.

A scheduling operation is initiated in response to a “scheduling event”. Scheduling events occur periodically with a predetermined interval given by the HRM scheduling period, $T_{p,rm}$.

The HRM scheduling model is based on the the following principles:

1. Wide slabs are rolled in the beginning of the scheduling period.
2. Narrow slabs are rolled in the end of the scheduling period, when the processing of wide slabs is complete.

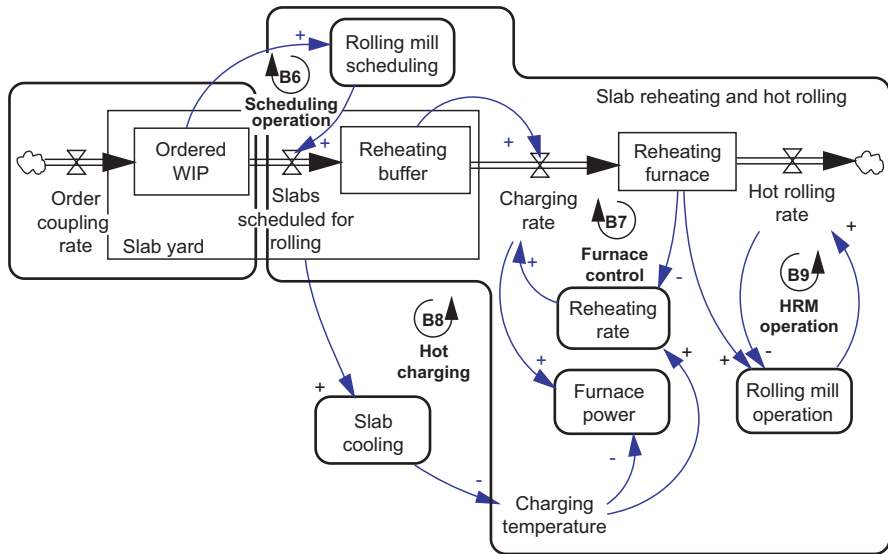


Figure 33: Policy structure diagram for slab reheating and hot rolling, including production scheduling of the rolling mill.

3. High-turnover product variants are rolled before low-turnover variants.

Similar to a dynamic scheduling environment which updates the schedule with real time information as it arrives [17], a static schedule is created from slabs available in the beginning of a scheduling period. The schedule is then updated in response to “rescheduling events” which occur periodically between scheduling events. During rescheduling the schedule is updated with newly arrived slabs that fit into the current schedule.

Dynamic scheduling is particularly useful when the plant operates with low levels of WIP, or when the output of the previous process step is unpredictable. Although this implementation lacks the event driven nature of a real real-time scheduling system, it improves the responsiveness of the scheduling operation in a similar way. Similar to the approach taken in Paper [80], the effect of a more dynamic scheduling policy can be assessed by changing the scheduling period as well as increasing the number of rescheduling events between scheduling operations.

5.4.2 The furnace control loop

The furnace control loop, Figure 33 (B7), controls the reheating rate depending on supply and current capacity of the reheating furnace.

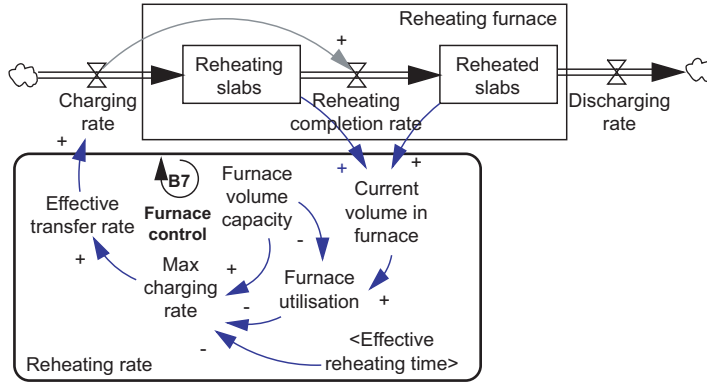


Figure 34: Model of reheating and furnace control with reheating modelled as a two-stage process.

Reheating is implemented as a two stage process using two level variables, “reheating slabs” and “reheated slabs” (Figure 34). These are linked by a first in/first out (FIFO) material delay. The delay time is the effective reheating time depending on the charging temperature for slabs that enter the furnace.

The charging rate is limited by the furnace volume capacity. The “max charging rate” is reduced when the furnace utilisation increases (i.e. when the furnace is almost full), thereby limiting the amount of material in the furnace.

Further, the reheating rate depends on the temperature gap between slabs charged into the furnace and the desired discharge temperature. The furnace model and its constituent equations is further described in Appendix A.

5.4.3 The hot charging loop

The reheating rate depends on the charging temperature (Section 5.4.2), which is computed in the hot charging loop, Figure 33 (B8).

An estimate of the charging temperature for slabs is made based on their residence time in the slab yard. An individual mean stock temperature is calculated for each product group. The order coupling rate is lower for low-volume products than for high volume products. Low volume products will therefore, on average, remain longer in the slab yard than high-volume products. Hence, slabs of low-volume products will on average be cooler than slabs for high-volume products.

When the mean temperature for a product group is calculated, it is assumed that all inventory is perfectly mixed. The reason why this model (introduced in Paper iii [80]) is used, is that it delivers consistent values of the transfer time for slabs from casting to rolling regardless of variations in throughput rate.¹⁰

Once the transfer time (“product lead time”, Figure 34) is known, the charging temperature can be calculated using an exponential function to describe the relation between between cooling time and temperature.

5.4.4 *The HRM operation loop*

Production in the hot rolling mill, i.e. the effective rolling operation, is controlled by the HRM operation loop, Figure 33 (B9). The main responsibility of the hot rolling operations loop is to initiate roll changes (setup).

A fundamental assumption has been that the total amount of setup is constant even though the duration of a single setup can change. Reduced setup time allows more frequent roll changes while the total amount of setup time is unchanged.

The maximum rolling rate [t/h] is given by the mean cycle time (time for hot rolling of one coil), and the mean slab weight. The effective rolling rate is then limited by downtime, setups, and the supply rate from the reheating process.

¹⁰ Little’s law [37], $CT = WIP/TH$, is often used to estimate the residence time, CT , for buffered material. However, when the outflow, TH , goes towards zero, the estimated residence time goes towards infinity. In the presence of discrete events such as setups and downtime, there will be variations in throughput rate that lead to undesired variations in the estimated cycle time.

5.4.5 Roll wear and roll changes

As already discussed, the level of process flexibility in HRM depends on the frequency of work roll changeovers. During a roll change, a fresh pair of work rolls are switched in and the old pair is sent to conditioning. The worn surface is removed to a depth that exceeds the depth of the wear marks. The frequency of work roll changes can be expected to influence the margin cost for work rolls, a problem that was investigated in Papers iv [81] and v [83].

Roll wear is a complex tribological process which is influenced by process parameters such as temperature, velocity, load and geometry, but also by the roll material and the rolled metal [54]. Still, after a transitory running in period, wear is approximately proportional to the rolled length [60]. It is therefore assumed that the radial wear can be estimated from a wear coefficient and the accumulated production in tonnes on a roll pair.

The model used in Paper v [83] is represented by the equation

$$\delta = \delta_0 (1 - \psi) + h\psi, \quad (5.5)$$

where δ_0 is a fixed standard grinding depth, ψ is a grinding efficiency coefficient and h the estimated roll wear. This is implemented in the roll wear and replacement model seen in Figure 35.

According to these assumptions, the roll grinding process can modelled as "dumb"¹¹, and remove a constant amount of worn surface material, or it can be assumed to be adaptive and remove material in proportion to the current amount of wear¹². Three cases are obtained, where the grinding depth, δ , is modelled as either

1. a fixed "standard" grinding depth,
2. proportional to the roll wear, or
3. a combination of a fixed and a proportional component.

All three cases can be obtained from Equation 5.5. The first case corresponds to $\psi = 0$, the second to $\psi = 1$, and the third to any intermediate value.

¹¹ This approach is used for the model in Paper iv [81] and for the "basic" model in Paper v [83].

¹² This approach is used in the "dynamic" model in Paper v [83].

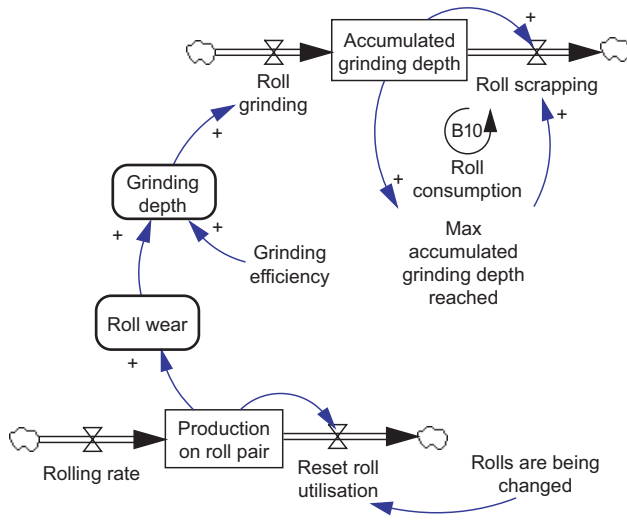


Figure 35: The roll wear and replacement model. Work rolls are worn during operation and a roll pair is conditioned after a roll change. The roll consumption loop (B10) keeps track of the accumulated wear on a pair.

5.5 SUMMARY

This chapter has presented the structure of an SD-based DPCM-model for the steel production system outlined in Chapter 2. The purpose has been to show how different parts of the production system work and interact. Using this model, it is possible to estimate resource consumption that occur in the included process models. It is also possible to study the combined effect of product range and process flexibility on system performance, which is the topic of Chapter 6.

SIMULATION ANALYSIS AND RESULTS

A number of simulation analyses were conducted during the course of this work. Some results were previously published in the appended papers. However, results concerning product variety have not been published before, and form the bulk of this chapter.

6.1 OVERVIEW

This chapter is structured as follows. Section 6.2 analyses the role of HRM–operations based on the early stages of model development. The analysis focuses on scheduling and setup time reduction in hot strip rolling. The contributions of energy consumption, WIP and tool wear (work rolls) to total mill economy are considered.

The initial results in Section 6.2 point to the need to include product variety in the analysis. This is the topic of Section 6.3 where the influence of process flexibility on performance is evaluated for a product range ranging from 25 to 500 variants.

Section 6.4 presents an attempt to operationalise the results. The chapter ends with a brief summary in Section 6.5.

6.2 INITIAL RESULTS

This section summarises the results of simulation analyses presented in Papers iii [80], iv [81] and v [83]. The individual contribution of each paper is summarised in Section 1.3.

A first simulation study was presented in Paper iii [80]. The model did at this stage implement five parallel product flows, but there was no mechanism to vary the number of product variants. Papers iv and v focused on process flexibility and used a continuous production flow without product variety, i.e. representing a situation where one plant produces one product.

When the results in Papers iv and v were compared to the results in Paper iii, it appeared that they exaggerated the possibility for performance improvement due to setup time reduction.

The later papers focused on modelling process flexibility and reheating, but used one aggregated flow for that excluded product variety. Several references state that product variety has a significant effect of production performance. At the same time empirical data on product range and order frequencies showed that in reality production is highly diversified (see Papers vi [5] and i [79]).

The results from Papers iii, iv and v pointed out some key areas for further improvement of the model. In addition to existing model capabilities, it should be possible to:

- Vary the number of product variants.
- Vary the distribution of customer order rates between product variants.
- Evaluate the influence of the batch size, setup times and scheduling practice in steelmaking.
- Account for the influence of product range on production capacity.

These improvement areas concern primarily the effect of product variety and the interaction between the steelmaking, casting and hot rolling processes. This led to the development of the model as presented in Section 5, which was used to produce the results in the following section.

6.3 INFLUENCE OF PRODUCT VARIETY

In response to the results discussed in Section 6.2, the model was improved to account for varying degrees of product variety. Four product groups, similar to “pseudo composite products” [89], were used as discussed in Section 5.3.1. During this stage the model evolved to the state described in Chapter 5.

This section presents a study of the combined effect of product variety and process flexibility. Process flexibility was evaluated by varying the following parameters:

- Target delivery delay (§6.3.1)
- Hot rolling mill (HRM) setup time (§6.3.2)
- Charge weight (§6.3.3)

Table 1: Simulation set-up for evaluation of contribution of target delivery delay to performance under varying product variety. See Figure 36 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 → 500	
Target delivery delay	D_D	1 → 5	weeks
Constants			
Charge weight	M	100	t
SCC setup time	$t_{s,cc}$	1	h
HRM setup time	$t_{s,rm}$	1	h

- Steelmaking—continuous casting (SCC) setup time (§6.3.4)
- Charge weight and SCC setup time (§6.3.5)
- HRM setup time, charge weight and SCC setup time (§6.3.6)

Each parameter was evaluated in a separate experiment as described in the sections indicated above.

6.3.1 Delivery delay

The target delivery delay, D_D , determines the size of the order backlog. As seen in Figure 32 (p.61), it is one of the parameters that determine the fraction of ordered material per charge. This section presents the results of varying D_D according to Table 1. The results, plotted in Figure 36, indicate the following:

- Longer D_D yields lower mean cost. The effect is stronger for high product variety (N).
- Longer D_D yields higher production capacity for high N.
- Longer D_D yields lower inventory (capital) cost at high N.
- Longer D_D yields lower reheating cost for high N.
- Furnace utilisation decreases rapidly with increasing N. After a minimum, it recovers somewhat. Recovery starts earlier for longer D_D

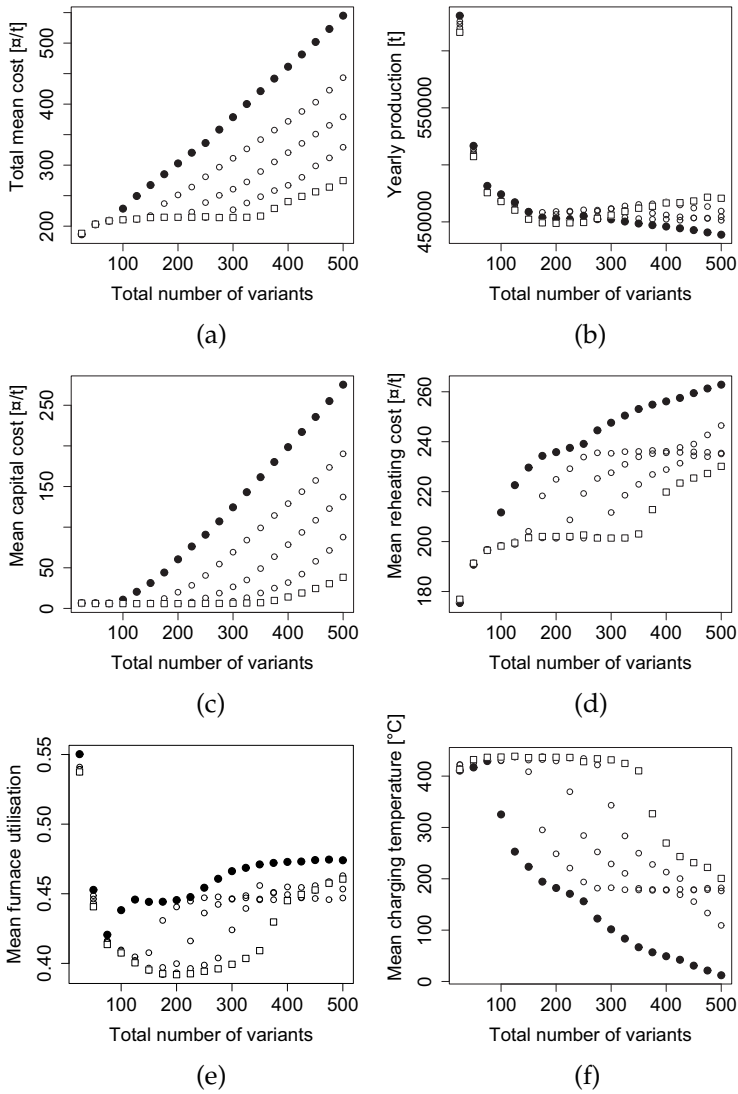


Figure 36: Results from evaluation of relation between product range, N , target delivery delay, D_D , and performance. Simulation set-up according to Table 1. (●) indicates $D_D = 1$ week, (□) indicates $D_D = 5$ weeks.

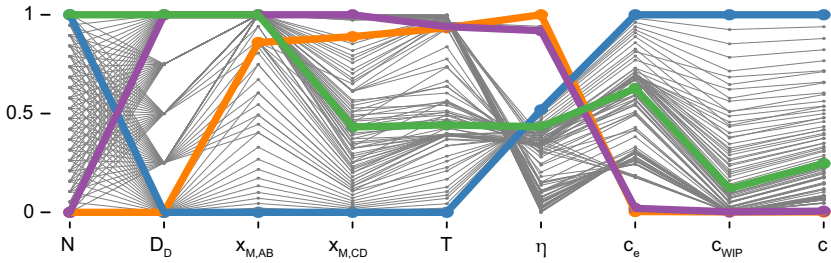


Figure 37: Parallel coordinate plot showing product variety, N , delivery delay, D_D , order fraction for groups, $x_{M,i}$, charging temperature, T , furnace utilisation, η , reheating cost, c_e , inventory cost, c_{WIP} , and mean cost per tonne, c .

- f. Charging temperature decreases rapidly after an initial plateau.

In general, performance deterioration is shifted to higher N for longer D_D .

A parallel coordinate plot of the results is seen in Figure 37. This plot shows relative values (0=lowest, 1=highest) of a number of variables. Four cases were highlighted to distinguish the results that correspond to max/min values of N and D_D .

It is seen in Figure 37 how low product variety is linked to high productivity and low costs. However, for high product variety the results differ depending on the target delivery delay.

When the delivery delay is long, customer orders for low turnover variants can accumulate for a longer time. This increases the order fraction per charge, which in turn yields less inventory, higher charging temperatures and lower corresponding costs than when the delivery delay is short.

6.3.2 HRM setup time

The purpose of this experiment was to evaluate the effect of reduced setup times in hot rolling as the number of product variants increased. This elaborates on the initial results, see Section 6.2, which showed that improved process flexibility in hot rolling had a significant positive impact on performance for low product variety.

Table 2: Simulation set-up for evaluation of contribution of setup time in hot rolling to performance under varying product variety. See Figure 38 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 → 500	
HRM-setup time	$t_{s,rm}$	0.2 → 1.6	h
Constants			
Charge weight	M	100	t
SCC setup time	$t_{s,cc}$	1	h

The model was set-up according to Table 2. The results are summarised in Figure 38. Referring to Figure 38 (a-f), a number of observations can be made:

- a. Cost per tonne increases almost linearly with product range. HRM setup time, $t_{s,rm}$, reduction reduces cost for low product variety.
- b. Production capacity declines rapidly as the number of variants increase.
- c. After an initial plateau, inventory (capital) cost increases almost linearly with product range. The effect of $t_{s,rm}$ is negligible.
- d. Reheating cost increases with product range. Two plateaus can be observed. Effect of $t_{s,rm}$ appears to be slightly stronger at low range.
- e. Furnace utilisation drops sharply with increasing N at low range, but then recovers slightly for $N > 150$. Low values of $t_{s,rm}$ yield low utilisation.
- f. Charging temperature decreases with N. Reduced $t_{s,rm}$ yield a significant temperature increase, particularly for low N. The effect diminishes as N increases.

For a narrow product range, there are few excess slabs and the size of the intermediate buffer is small. The slab cooling time and the amount of WIP is mainly determined by the HRM

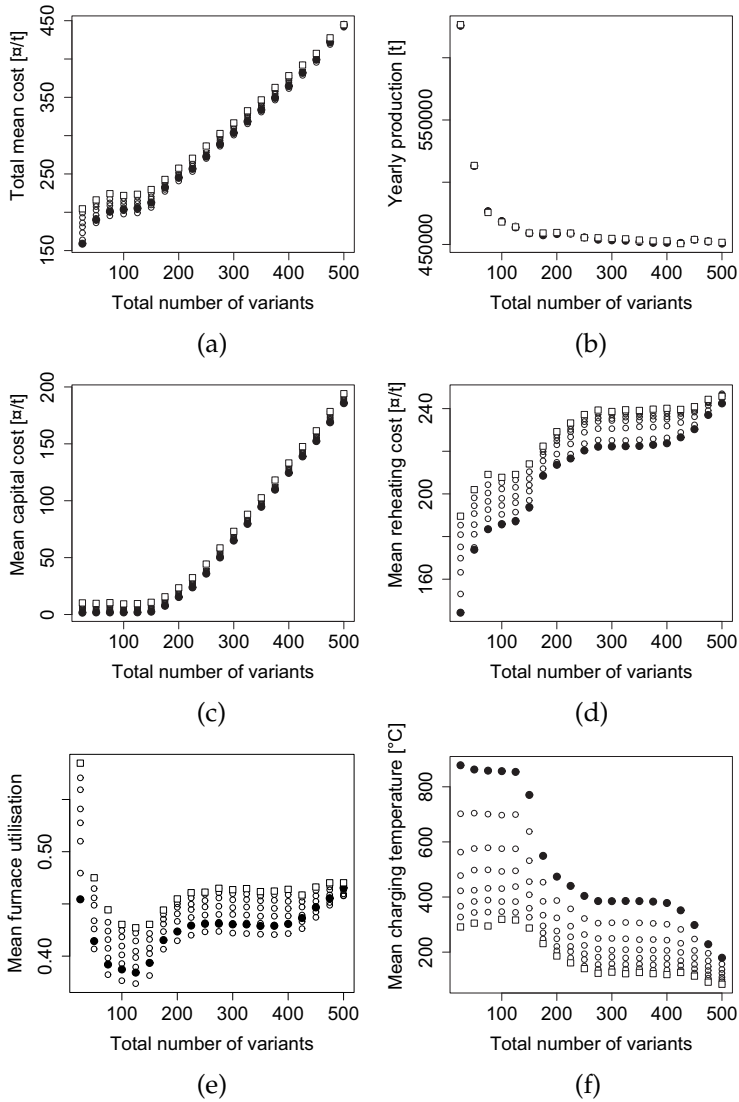


Figure 38: Results from evaluation of relation between product range, N , HRM setup time, $t_{s,rm}$, and performance. Simulation set-up according to Table 2. (●) indicates $t_{s,rm} = 0.2h$, (□) indicates $t_{s,rm} = 1.6h$.

Table 3: Simulation set-up for evaluation of contribution of charge weights to performance under varying product variety. See Figure 39 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 → 500	
Charge weight	M	25 → 250	t
Constants			
HRM setup time	$t_{s,rm}$	1	h
SCC setup time	$t_{s,cc}$	1	h

scheduling process ¹. Therefore, costs for reheating and inventory are reduced simultaneously when the setup time (and HRM-schedule length) is reduced.

As the number of product variants increases, the order rate for each product goes down and the fraction ordered quantity per charge decreases (see Section 5.3.3) — the time that unordered slabs are kept in stock must be superimposed to the delay from HRM scheduling. Reheating cost and capital cost increase and outweigh a potential positive contribution from HRM scheduling.

6.3.3 Charge weight

This section evaluates the effect of batch size (charge weight, M) for constant CC setup time, $t_{s,cc}$. The model was set-up according to Table 3. The results are summarised in Figure 39.

Referring to Figure 39 (a-f), the following observations can be made:

- a. Increasing charge weight, M, yields a dramatic cost increase for high product variety. Maximum cost for N = 500 is about 850 Q/t compared to about 450 Q/t in Figure 38. Capacity decreases with increasing N.
- b. Small charges yield a drastic reduction in capacity for N > 25.

¹ It is assumed that $t_{s,rm}/T_{p,rm} = \text{const}$, since rapid setups allow short schedules without loss of production capacity. See Paper iv [81] and Section 5.4.1, p.61.

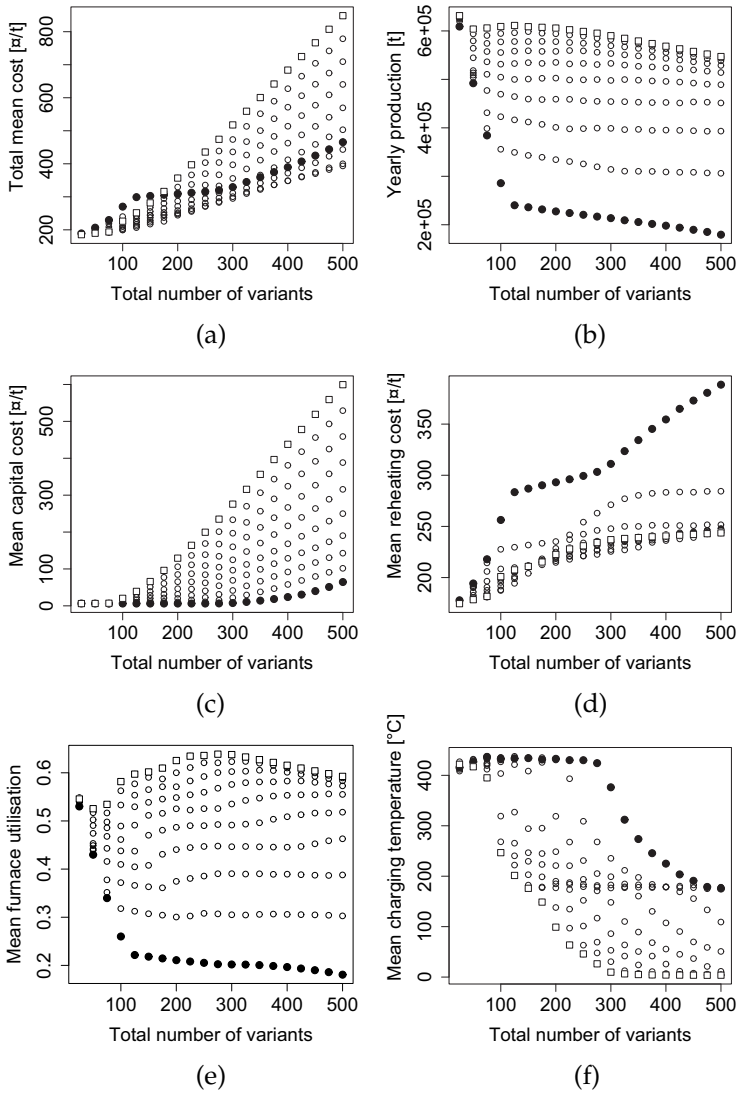


Figure 39: Results from evaluation of relation between product range, N, charge weight, M, and performance. Simulation set-up according to Table 3. (●) indicates M = 25t, (□) indicates M = 250t.

Table 4: Simulation set-up for evaluation of contribution of SCC set-up time to performance under varying product variety. See Figure 40 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 → 500	
SCC setup time	$t_{s,cc}$	0.25 → 1.5	h
Constants			
Charge weight	M	100	t
HRM setup time	$t_{s,rm}$	1	h

- c. Large batches yield high inventory (capital) cost. For $N = 500$, 250 t batches yields approximately a threefold cost increase compared to Figure 38c. The best case, 25 t, largely eliminates capital costs.
- d. Larger batches yield lower reheating cost.
- e. Larger batches yield higher furnace utilisation.
- f. Smaller batches yield higher charging temperature.

The poor capacity for small charge weights is due to the assumption $t_{s,cc} = 1\text{h}$, resulting in high fractions of setup time except for low product variety. This yields low furnace utilisation which in turn results in high reheating cost.

The case $M = 25\text{t}$ (●) yields lowest inventory cost but highest reheating cost. Downsizing the reheating furnace can improve furnace utilisation and hence the furnace efficiency.

Increasing M improves capacity at the expense of dramatically increased capital costs for high product variety. This is compensated to some extent by reduced reheating costs due to better furnace utilisation.

6.3.4 SCC setup time

The previous section looked at the effect of varying charge weight M for constant setup time $t_{s,cc}$. In this section $t_{s,cc}$ is varied for constant M . The model was set-up according to Table 4. The results are summarised in Figure 40.

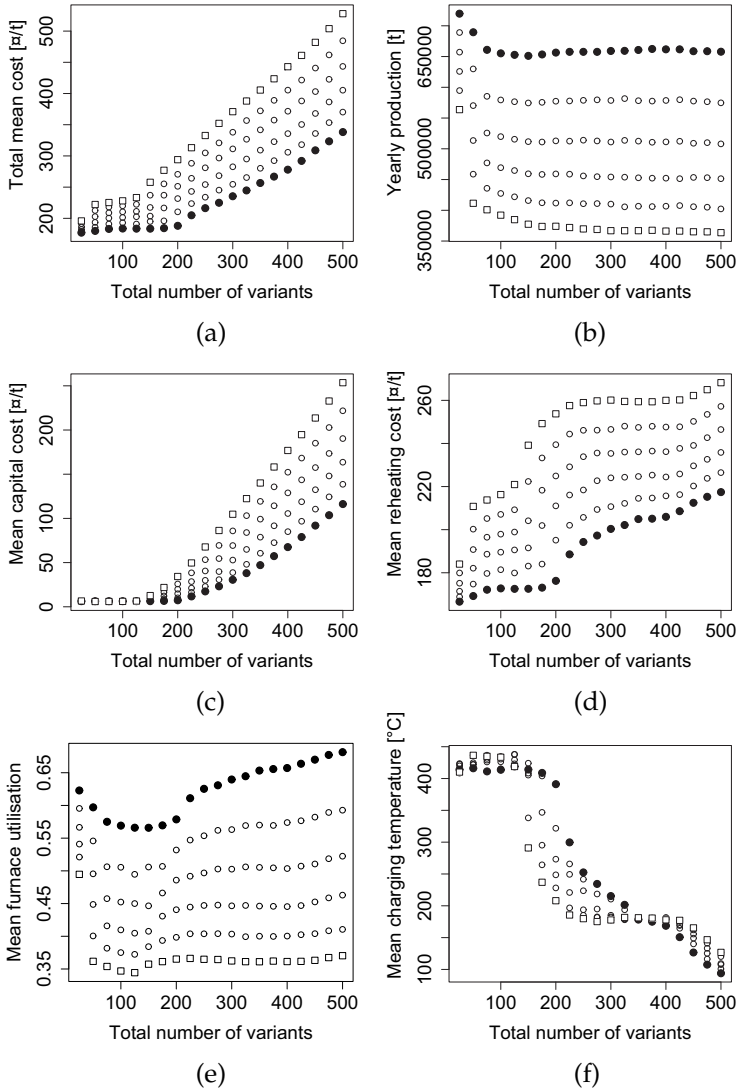


Figure 40: Results from evaluation of relation between product range, N , SCC setup time, $t_{s,cc}$, and performance. Simulation set-up according to Table 4. (●) indicates $t_{s,cc} = 0.25h$, (□) indicates $t_{s,cc} = 1.5h$.

Again, a number of observations can be made. Referring to Figure 40 (a-f), it is found that:

- a. Reduced $t_{s,cc}$ yields a cost reduction, particularly for high product variety.
- b. Reduced $t_{s,cc}$ increases production capacity.
- c. Capital cost increase with product range to the same level as seen in Figure 38. There is an improvement for low $t_{s,cc}$, although not to the extent seen in Figure 39.
- d. Long $t_{s,cc}$ yield high reheating cost.
- e. Long $t_{s,cc}$ yield low furnace utilisation.
- f. $t_{s,cc}$ has no significant impact on charging temperature.

Comparing Figure 40b with Figure 39b, it is seen that reduced $t_{s,cc}$ can yield the same capacity improvement as increased M . This is advantageous for high product variety since the need to stock additional unordered slabs can be eliminated.

6.3.5 Charge weight and SCC setup time

The experiment presented in this section varies the charge weight, M , and SCC setup time, $t_{s,cc}$, simultaneously. M and $t_{s,cc}$ are chosen such that the processing time for one charge is equal to $t_{s,cc}$. Thus, an effective processing time for a 100 t charge of $t_{p,cc} = 1\text{h}$ yields $t_{s,cc} = 1\text{h}$. Parameters were chosen according to Table 5 with the results summarised in Figure 41.

It is seen in Figure 41 (a-f) that:

- a. Cost increases almost linearly with range. The increase is stronger for large M . For a narrow product range, cost is independent of M .
- b. Capacity decreases rapidly with increasing N for large M . The decrease is less abrupt for small M .
- c. The increase in cost is dominated by inventory costs for large M .
- d. Reheating costs increase with N , particularly for large M .

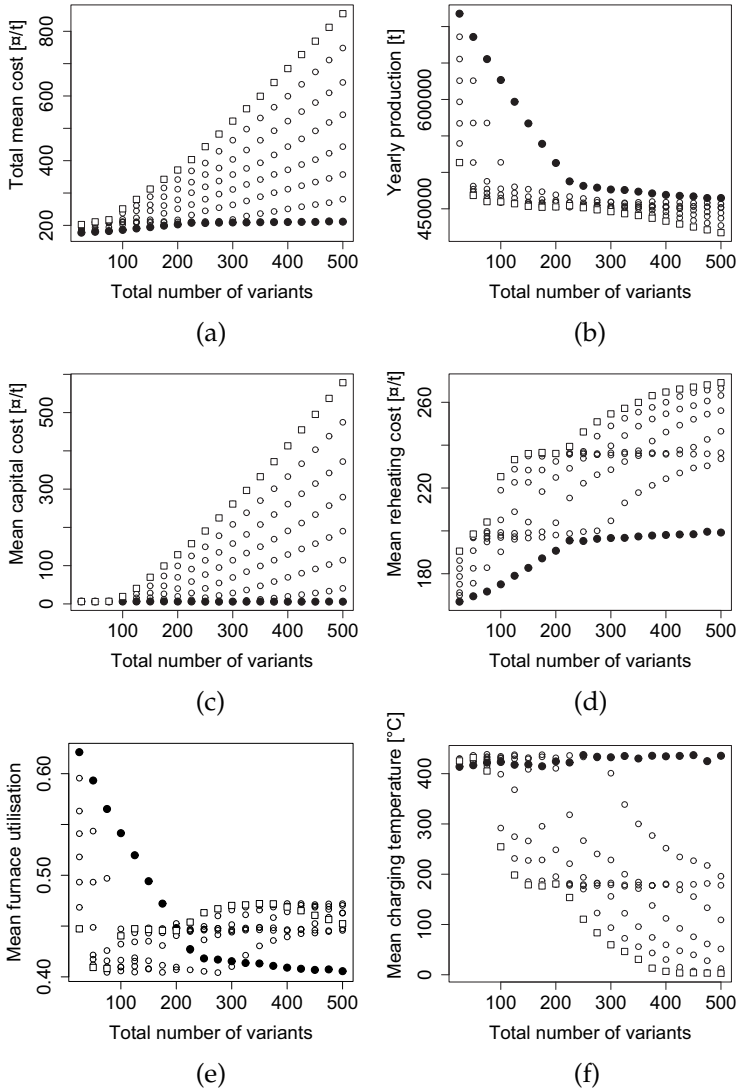


Figure 41: Results from evaluation of relation between product range, N , charge weight, M , SCC setup time, $t_{s,cc}$, and performance. Simulation set-up according to Table 5. (●) indicates $M = 25t, t_{s,cc} = 0.25h$, (□) indicates $M = 200t, t_{s,cc} = 2h$.

Table 5: Simulation set-up for evaluation of performance when charge weight and SCC setup times were varied simultaneously in combination with varying product range. See Figure 41 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 \rightarrow 500	
SCC setup time	$t_{s,cc}$	0.25 \rightarrow 2	h
Charge weight	m	25 \rightarrow 200	t
Constants			
HRM setup time	$t_{s,rm}$	1	h

- e. Furnace utilisation is high for a low N but decreases as N increases.
- f. Charging temperature is about 400°C for a small N. It remains at this level for $M = 25t$.

The production capacity is approximately equal for all cases which is expected according to the experiment set-up in this case.

6.3.6 HRM setup, small charges and rapid SCC setup

From the previous section it was seen that low charge weight in combination with rapid SCC setups largely eliminated slab inventory and capital cost for all ranges. At the same time charging temperatures remained moderately high even at high product variety.

In this section, another experiment is conducted where the case $M = 25t$, $t_{s,cc} = 0.25h$ from the previous section is used as a starting point — the influence of setup time reduction in hot rolling is evaluated for the case of a highly flexible slab production. The model was set-up according to Table 6. The results are summarised in Figure 42.

Figure 42 (a-f) show that the combined effect of efficient small lot production in steelmaking and continuous casting with improved process flexibility in hot rolling improves performance significantly:

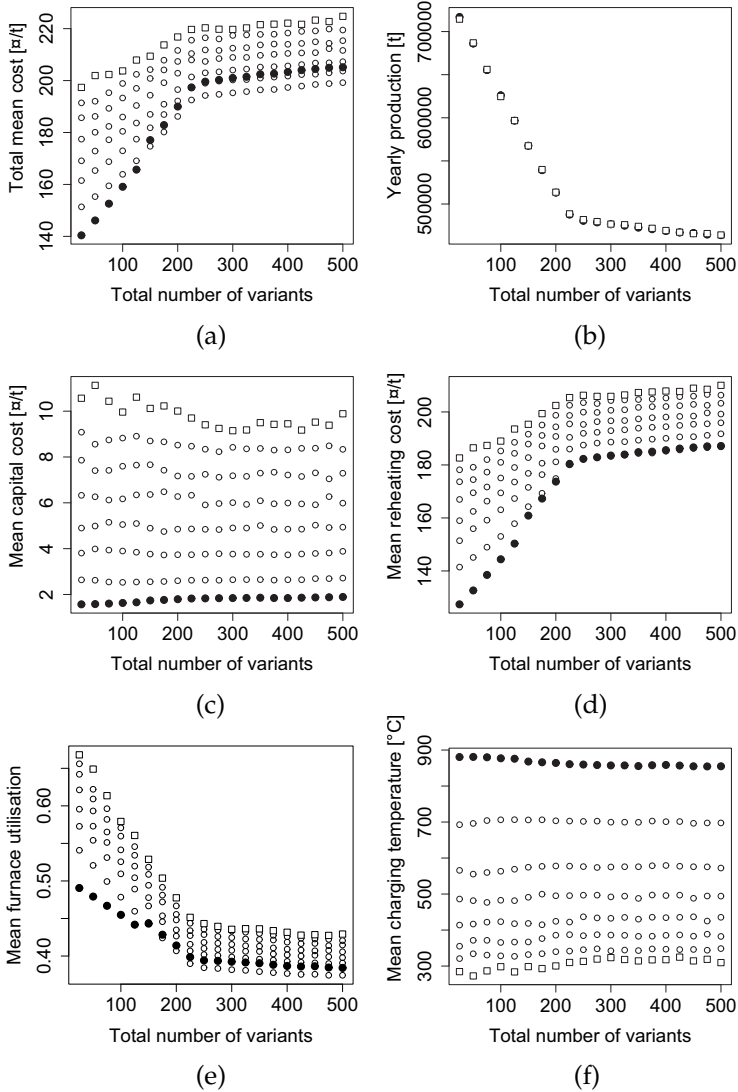


Figure 42: Results from evaluation of relation between product range, N , and HRM setup time, $t_{s,rm}$ in combination with efficient small lot production in SCC. Simulation set-up according to Table 6. (●) indicates $t_{s,rm} = 0.25h$, (□) indicates $t_{s,rm} = 1.5h$.

Table 6: Simulation set-up for evaluation of contribution of SCC set-up time to performance under varying product variety. See Figure 42 for results.

Parameter	Symbol	Value	Unit
Number of variants	N	25 \rightarrow 500	
HRM setup time	$t_{s,rm}$	0.25 \rightarrow 1.5	h
Constants			
SCC setup time	$t_{s,cc}$	0.25	h
Charge weight	M	25	t

- a. Cost increases with product range. Improved HRM flexibility yields best cost reduction for low product variety.
- b. Production capacity is not influenced by HRM setup time. (This result corresponds to the case $M = 25t$, $t_{s,cc} = 0.25h$ in Figure 41b.)
- c. Inventory cost is nearly negligible for all cases but lowest for $t_{s,rm} = 0.25h$.
- d. Reheating cost increases with product range. Improved HRM flexibility reduces reheating costs, particularly at low range.
- e. Furnace utilisation is high for low product range but decreases with increasing range.
- f. Charging temperature is independent of N and increases with decreasing $t_{s,rm}$.

Improved HRM flexibility yields the best cost reduction results for low product range, but has a positive impact on performance at all ranges.

This experiment shows that the charging temperature is determined by the process flexibility of the rolling operation in the absence of excess slabs.

6.4 SYNTHESIS

The following section presents an attempt to capture some characteristic features of the results in Figures 38–42:

- Why does several measures display exponential change towards stable “plateaus”?
- What determines the location of “knees” where derivatives change abruptly or plateaus end?
- Why is there an initial drop in furnace utilisation?
- Why does furnace utilisation recover for large N ?

Three measures are addressed: charging temperature (Figure 43a), furnace utilisation (Figure 43b) and reheating cost (Figure 43c).

Starting with the variations in charging temperature, Figure 43a shows a generalised plot of temperature, T , versus product range, N . From a maximum T_1 at the plateau (1), there is a decline in two stages (2,3). Stage (2) lasts from N_1 to N_2 and stabilises towards a plateau at T_2 . During stage (3), starting from N_2 , the decline continues towards the ambient temperature T_a .

This behaviour occurs as the order fraction of low volume (C/D) variants is gradually reduced during stage (2). During stage (3) the effect is reinforced due to a reduction in the order fraction of high volume (A/B) variants. The decline continues gradually towards the ambient temperature.

The maximum temperature T_1 depends on the minimum transfer time from casting to hot rolling for ordered slabs. As discussed in Paper iv [81], the mean transfer time is equal to the scheduling period $T_{p,rm}$ assuming decoupled operation of meltshop/CC and HRM and that all slabs must be physically available in the slab yard before they are scheduled for rolling.

The characteristic temperature T_2 depends on the range and volume fractions of high versus low volume products given by the order frequency distribution. T_2 occurs when the order fraction for low volume (C/D) variants is at its minimum, i.e. for example one slab out of five in one charge. However, the order fraction for high volume (A/B) variants is still 100%.

The value of N_1 depends on the ratio of time between production times for low volume products, $T_{BPT_{C/D}}$, to the program duration in meltshop/CC, $T_{p,cc}$.

The value of N_2 depends on the ratio of time between production times for high volume products, $T_{BPT_{A/B}}$, to the program duration in meltshop/CC, $T_{p,cc}$.

Another factor that determines the efficiency of reheating is the furnace utilisation. Figure 43b captures its dependency on

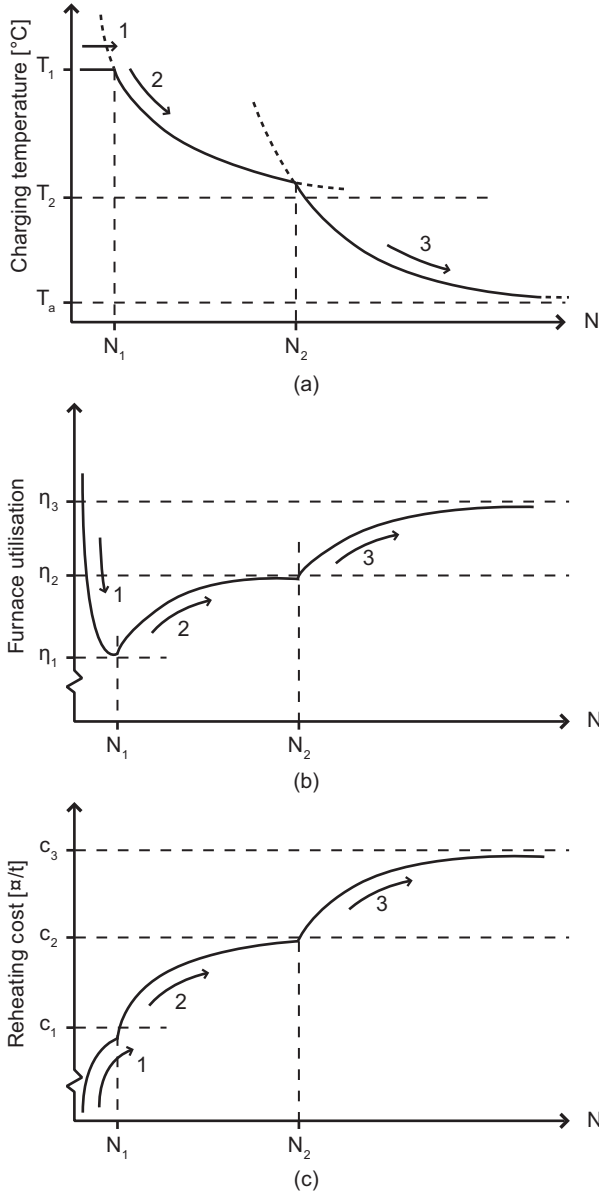


Figure 43: Operationalisation of the results with some characteristic processes for different product ranges indicated. All production is to customer order for low product variety (a). Order fractions for low volume variants decrease (b). Order fractions for high volume variants decrease (c).

product variety. As seen in this plot, there is a sharp drop in furnace utilisation as N increases in stage (1). The fraction of setup increases during this stage — a process that corresponds to a reduction of the sequence factor. Furnace utilisation decreases during this stage, which yields an increasing reheating cost that approaches c_1 in Figure 43c. This process continues even though the charging temperature remains high (T_1 in Figure 43a).

Then, starting from N_2 the furnace utilisation starts to increase. This happens since the charging temperature is going down. When this happens, the need for reheating increases leading to a longer mean furnace cycle time.

However, the decrease in charging temperature during stage (2) causes the reheating cost to continue to increase despite an increasing furnace utilisation. During this stage, cost is gradually approaching c_2 (Figure 43c).

The temperature drop is accelerating during stage 3, and furnace utilisation increases in response to this change. However, the temperature reduction is dominating in this case and the reheating cost continues to approach c_3 .

6.5 SUMMARY

To summarise, this analysis shows that production performance is highly dependent on the level of product variety. Capital costs and reheating costs increase as soon as there WIP accumulate due to the presence of unordered slabs. This increase is almost linear as seen in e.g. Figures 36 and 38 (a).

From Section 6.3.2 it was seen that improved process flexibility in hot rolling results in a significant performance improvement in the case of low product variety. However, this effect decreased with increasing product variety. On the other hand, Sections 6.3.3–6.3.5 showed how improvements in upstream flexibility (reduced charge weight, short SCC setup times) contributed greatly to reduced costs in the case of high product variety.

Plants configured for high product variety should be equipped with flexible processes in order to handle the frequent changeovers required. The results in this chapter suggest that much of the cost penalty for high product variety can be eliminated.

A high-variety producer that use a plant that was conceived for low product variety must make a trade-off between product variety, cost and dependability. This is illustrated by Figure 44,

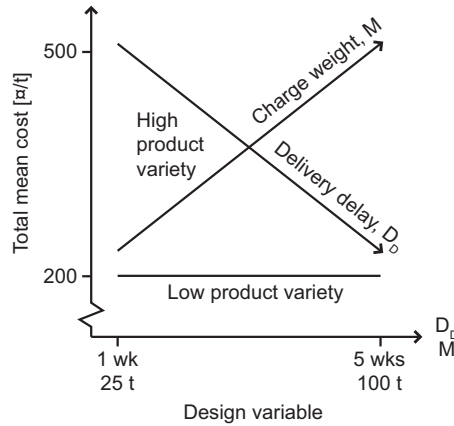


Figure 44: Trade-off between dependability, process flexibility and mean margin cost per tonne for reheating and in-process inventory.

which shows how production cost is influenced by the delivery delay, D_D , and the charge weight, M . To summarise, low cost diversified production is possible, either through implementation of flexible processes, or at the expense of long delivery lead times.

Cost and dependability are two out of four dimensions of competitive priority that are frequently used in the literature. The other are quality and flexibility, where flexibility refers to volume flexibility, i.e. the ability to handle variations in customer demand. It would be interesting to extend this analysis to account for the impact on quality and flexibility. However, this requires that the model is further developed.

Models for estimation of the benefit of process flexibility related investments found in the literature are generally dealing with determination of optimal setup times. In general, these models focus on finished goods inventory and neglect the influence of WIP-induced costs [55]. This chapter has shown that the models presented in Chapter 5 can be used for estimation of the economic savings potential due to more flexible processes. These models account for variations in WIP as well as reductions in energy consumption, and can easily be augmented to estimate CO_2 emissions. This is important since it has previously been difficult to quantify the benefits of investments in process flexibility.

DISCUSSION AND FUTURE RESEARCH

This chapter returns to the research questions and attempts to summarise the findings. A short summary of the findings is given in Section 7.1. Each sub-question is then discussed in a separate section — RQ1 in Section 7.2, RQ2 in Section 7.3, and RQ3 in Section 7.4. The thesis is closed with some concluding remarks in Section 7.5 and a critical review and suggestions for future research in Section 7.6.

7.1 RESEARCH QUESTIONS REVISITED

The findings of this thesis can now be summarised to answer the main research question and the three sub-questions which were formulated in Chapter 1.

Starting with the main research question:

RQ0: *How can steel producers combine a strategy based on a diverse highly value-added product mix with the need for continuously lowered production costs?*

Process flexibility is a key enabler for improvement of production performance in steel plants in the case of high product variety. Process flexibility requirements must be evaluated for major investments. However, small incremental changes in daily continuous improvement work often have an adverse effect on process flexibility. In these circumstances there is neither time nor resources available for systematic analysis. The adverse effect of poor process flexibility on performance in high-variety steel production must be universally and intuitively understood throughout the organisation, e.g. by management, production engineers and product developers. A strategy process that focuses on organisational learning and development of shared vision that recognises the enabling role of process flexibility is central in order to align intended and emerging strategies for production improvement.

Then, continuing with the three sub-questions:

RQ1: *Design of a method for assessment of the relation between product variety, process flexibility and production performance.*

This was successfully assessed using the proposed system dynamics-based dynamic process cost modelling (DPCM) method. A three layered model structure that target production processes, production operations and resource cost is proposed. Aggregated product flows (“pseudo composite products” [89]) allow product variety to be incorporated in the model.

RQ2: *Characterisation of the relation between production configuration and performance with consideration of product variety.*

High product variety and order volumes less than the minimum batch size in steelmaking—continuous casting (SCC) result in excess slabs and build-up of in-process inventory. Consequently, there is an increase in reheating cost as well as inventory cost. Upstream process flexibility improves performance for high product variety, while downstream process flexibility improves performance for low product variety. Increased delivery delays can reduce production cost at the expense of increased customer order lead times.

RQ3: *The use of proposed methods, models and findings in the firm’s strategy process.*

The paths of deliberate and emergent strategy should be aligned such that process flexibility requirements are contemplated for major investments as well as in daily continuous improvement work. Identification of strategic capabilities and development of corresponding operational capabilities are central. Model based learning, e.g. based on the proposed five step framework can aid this process.

This summary is elaborated in the following, where each sub-question is targeted in a separate section.

7.2 RQ1 — ASSESSMENT METHOD

The design of a method for assessment of the relation between product variety and production performance depends on the purpose for which it is developed. For the scope of this thesis, the main purpose is learning. Focus is on high-level understanding and behaviour of production under different market conditions.

Economic aspects are the main drivers for investment in new technology or operational practice. The SD-based DPCM framework proposed in Chapter 4 allows an integrated analysis of production system design and production cost. This approach, which rely on modelling, simulation and exploratory model testing, encourages high-level learning.

The purpose has not been to come up with detailed plans for improvement. More important is that users of the method develop an understanding for how different types of change can be expected to influence performance in a general case.

This analysis must include sufficient detail that the impact of processes, information systems and operations can be addressed and estimated. Models must be sufficiently detailed that the effect of a direction of change becomes clear.

The dynamics of a production system is to a large extent determined by the interfaces between process steps. Process flexibility, information feedback loops and how the design of one process step influences the next are examples of factors that determine overall behaviour.

Models conceived to capture the dynamics in interfaces between process steps, which are normally considered in isolation, will likely be fairly complex. This thesis includes process models, operational models, planning models, customer order handling models, and more. Knowledge from different fields must therefore be combined in a cross-disciplinary way.

Models often become too complex for communication purposes. Hierarchical decomposition and partitioning of models through the use of multiple policy structure diagrams is therefore encouraged. The structure and causal loops of the full model can then be preserved while unnecessary detail is hidden.

The main threshold for application of the proposed method is probably not related to modelling techniques or modelling and simulation skills. Instead, the complexity and cross-disciplinary nature of the problems that are targeted can be hard to overcome. Further research on industry specific production models for steel production is therefore needed to provide a basis for applied use.

For mature industries like the steel industry the rate with which production technology that dramatically alters the competitive situation is introduced slows down. This means that production technology and operational practice tend to be similar across the industry.

At least for the steel industry, it seems plausible that models that were developed for a class of plants can be reused by many firms. A “catalogue” of reusable models, similar to the concept of design patterns in computer software engineering [30] can be conceived. However, this thesis is not an attempt to compile such a catalogue. Instead, it is merely a foundation for future research in this area.

Similar to design patterns, reusable production models would require a high degree of abstraction. Patterns can then serve to suggest solutions to similar problems though they will not be directly applicable as solutions in themselves. Instead, a pattern must be enriched with detail that makes it useful for a specific purpose. When the purpose of analysis changes, so will the model, although the overall structure may remain intact.

7.3 RQ2 — EFFECT OF PRODUCT VARIETY

In general, a niche market steel producer will seek to reduce production cost while maintaining a diverse product mix. The tendency is rather towards increased product range and lower order quantity per variant than towards standardisation and high volumes. This process, the author believes, will continue. In the future it will be ever more important to supply small quantities directly to customers without incurring additional cost.

The results show the strategic importance of developing the right operational capabilities. The concepts of Figure 9 can be used to illustrate how operational capabilities determine the position of the competitive frontier. This is seen in Figure 45, where the effect of upstream and downstream flexibility is seen for different product ranges.

Figure 45 summarises the following conclusions:

- Plants with poor upstream and downstream flexibility operate on the frontier A_1B_1 .
- Improvement of downstream flexibility pushes down the frontier for low N (A_2B_1).
- Improvement of upstream flexibility pushes down the frontier for high N (A_1B_2).
- Improvement of both upstream and downstream flexibility pushes down the frontier for all N (A_2B_2).

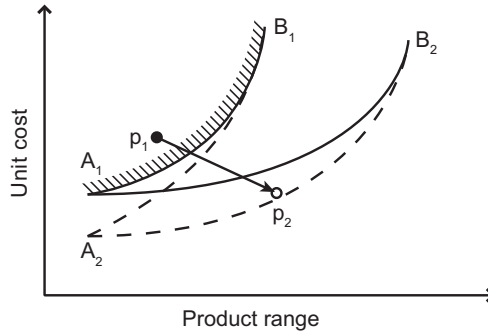


Figure 45: Influence of upstream versus downstream flexibility on position of competitive frontiers.

This means that a plant operating at position p_1 in Figure 45 can improve its operational capabilities such that an increased product range can be produced at reduced production cost, corresponding to a move to position p_2 . There is an evident link between operational and strategic capabilities that can be exploited by a firm that possesses the required knowledge within product and process engineering. Moreover, the strategic significance of Shingo's work on systematic setup time reduction is clear, and SMED should be applied in steel industries.

This results can be generalised:

- *Low product variety:* Performance is improved when the production system exhibits a high degree of process flexibility *downstream* from the order coupling point.
- *High product variety:* Performance is improved when the production system exhibits a high degree of process flexibility *upstream* from the order coupling point.

As an example, consider a low-variety producer where slabs are fed to a hot strip mill directly from continuous casting. Everything is produced to customer order and there are no excess slabs. In this case, the potential for hot charging is entirely dependent on the flexibility of the rolling mill. Unless slab production and hot rolling is synchronised, coffin-type scheduling will have a detrimental effect since newly cast slabs must be buffered until they fit into the HRM schedule.

On the contrary, a high-variety producer will have to store excess slabs, which means that some fraction of production cannot

be hot charged. The solution is to reduce the feasible batch size in steelmaking and continuous casting. In this case, conventional methods such as SMED can be used to reduce setup times, but it may also be necessary to consider whether existing continuous casting processes are optimal for the plant in question. Ingot casting may be an alternative, but interesting new technologies such as mould metallurgy (Bentell et al. [5]) that may improve the flexibility of metallurgical processes and casting are also emerging.

Low cost diversified steel production can be accomplished since improved process flexibility yields better resource efficiency. Hence it is possible to simultaneously reduce cost and reduce environmental footprint. This requires the development of new flexible process technologies that can meet the high quality requirements of special, high strength and stainless steel production. Additionally, traditional process and production engineering must consider process flexibility also for minor improvements since the accumulated effect of many small changes has a significant strategic impact.

7.4 RQ3 — IMPLICATIONS FOR STRATEGY FORMATION

Traditional production engineering and process development focus on individual process steps, while the interfaces between process steps are largely ignored. This is reflected by the departmentalisation of education in universities, and by the organisational structure of firms.

If the strategic goal is diversified low-cost “value-added” steel production, there will be certain capabilities that are recognised as strategically important. However, these strategic capabilities represent only the top of the iceberg of a hierarchy of increasingly operational capabilities needed to reach this goal. In the end, it is understanding of how operational capabilities interact, combine and propagate up the hierarchy that provides the means to develop a strategy with high probability of realisation. Interactions between process steps are therefore highly significant.

Since any realised strategy is likely both deliberate and emergent, it is important to address both realisation mechanisms in the strategy formation process. Emergent strategy is the accumulated effect of uncoordinated efforts throughout the organisation over time. Management has limited possibilities to control or

direct these efforts directly. Instead, it is necessary that a long-term perspective on organisational learning is adopted in order to improve capability awareness and reduce the gap between perceived and effective capability requirements.

Learning is not a one-off event. This is particularly true when we refer to the development of new knowledge, which cannot be analysed into being based on known premises. As discussed earlier in this thesis, it is necessary to stimulate ongoing and cross-disciplinary learning in areas that are thought to have strategic significance.

This learning process can benefit from the type of dynamic process cost modelling (DPCM)-based analyses that are presented in this thesis.

The five step framework puts improvement of capability awareness at the centre of DPCM. Capability awareness is central in the strategy process as discussed in Chapter 4, and modelling and insights provided by DPCM models fit neatly into this process. This is further illustrated by the elaborated strategy process model shown in Figure 46.

Figure 46 shows three causal loops interact in the strategy process. The emergent strategy loop (B1) represents the evolution of new or improved capabilities from problem solving. The types of solutions that are employed by operators, engineers, or kaizen/improvement teams, depend on the prevalent perception of what needs to be done.

The deliberate strategy loop (B2) represents development of capabilities through formal strategic decisions.

The perception of the capability gap influences the formation of both deliberate and emergent strategy. Further, the perceived capability gap influences the type of business strategy that firm management is likely to adopt. The choice of business strategy has implications for the choice of market and the market requirements that will follow.

Models that clarify the impact of product variety contribute to reducing the gap between the effective and the perceived capability gaps, thereby improving the quality and suitability of solutions applied at all levels.

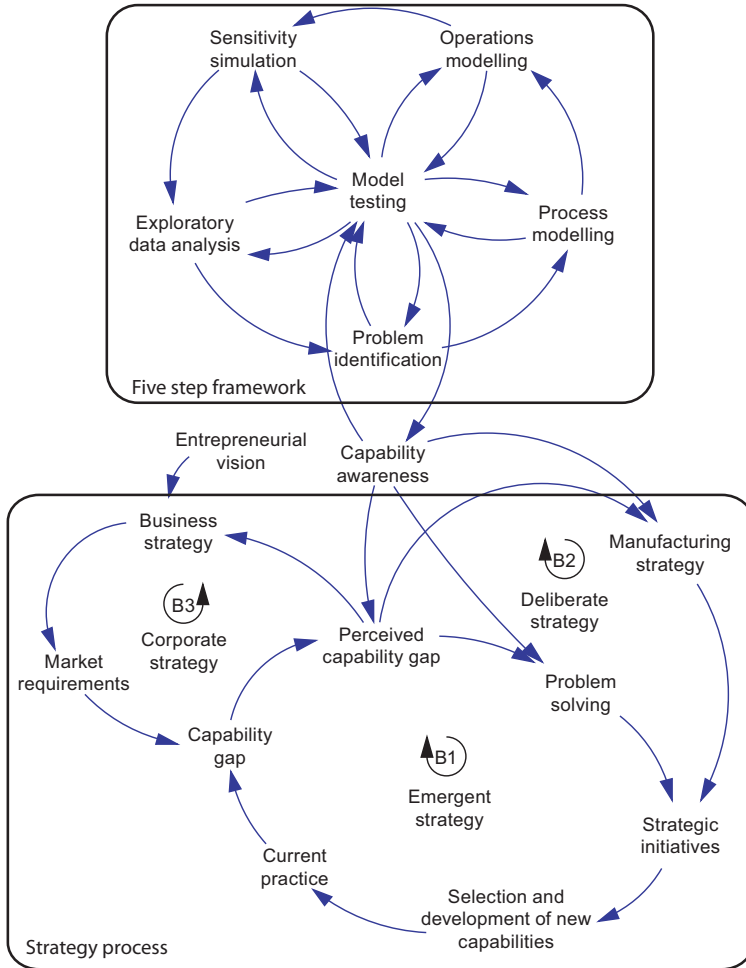


Figure 46: Extended strategy process model that incorporates the five-step framework. The strategy model consists of the emergent strategy loop (B1), the deliberate strategy loop (B2), and the corporate strategy loop (B3). All of these loops are influenced by the perceived capability gap.

7.5 CONCLUDING REMARKS

This thesis illustrates how steel producers that choose to pursue different strategic investments will enter different improvement trajectories. It is clear that capability awareness and the per-

ception of the capability gap will influence a firm's potential to maintain the required dynamic fit between capabilities and market requirements. In order to obtain operational excellence firms must look to creative exploitation of process and operations improvements beyond current technologies or "best practice" solutions.

It has been argued that "in a production system the molecular scale could be of environmental interest and of interest at some material processing activities; however, the molecular scale is unlikely of interest for any other point of view" (Bjelkemyr [7, p.12]). This may apply in some cases, but in general, the opposite is true. For example in hot rolling, process features such as reheating rates, number of mill stands, number of passes, time between passes, reduction in each pass and the subsequent cooling rates, are factors that determine plant characteristics on a macro scale. At the same time, they are determined by processes on the micro scale, including for example grade compatibility, weldability, heat transfer, nucleation, grain growth, recrystallisation, precipitation and phase transformations.

Hence, processes on the molecular and micro scales imply the macro structure of the production system, and are thus important determinants of overall behaviour. When these links are understood, it is possible to conceive improved production methods that simultaneously yield desired product properties and high (system) performance.

Much "friction" and waste appears due to buffering in the interfaces between process steps. Some examples of initiatives that can reduce the need for buffering include to

- reduce setup times, e.g. between stop and restart of CC;
- reduce yield losses due to transient processes; e.g. during a change of width or grade in CC;
- improve process control and eliminate manual inspection between process steps, e.g. using CAQC systems;
- eliminate all constraints on product sequence that existing scheduling systems seek to optimise.

The limits of what can be accomplished using known processing technology and operational methods defines the competitive frontier in a business. Most steel producers use similar process

technology which is operated in largely the same way. This means that two plants, with the same production capabilities, that are positioned on different ends of the product range scale will perform differently. Typically, the plant with a more diversified product mix will perform worse. However, by targeting the causes of poor process flexibility, as discussed above, high-variety producers can eliminate some or all of this cost penalty.

As noted by Slack and Lewis [76, p.156], the strategic implications of investments in process technology is often far greater than merely cost reduction. Competitive frontiers are not static, and innovative firms can redefine their competitive environment. New frontiers open up with the emergence of previously unknown processing technology and operational methods. Well known examples are the development of the Bessemer converter, the continuous caster and scrap-based mini-mills.

But most production improvements do not open up new competitive frontiers. Instead, they reduce the gap between the possible and the effective capabilities for an existing type of production system.

Figure 47, compiled from Paper ii [82], illustrates that the structure of a production system reflects the capabilities of the processing technology in use. It is not possible to impose a production system structure that is not fit to the capabilities of the technology and methods in use. Hence, moving towards the increasing levels of integration seen in Figure 47 can only be accomplished either through reduction of flexibility requirements by reduced product variety or through investments in more flexible processing technology.

Operational methods evolve such that equipment is used as efficiently as possible, based on current knowledge. However, there are limits to what can be accomplished through optimisation if the processing technology remains unchanged. Thus, standard technology and "best practice" operational methods force steel plants to run meltshop/CC as decoupled units separated by a slab yard.

Development of advanced scheduling methods in steel making, continuous casting and hot rolling represent attempts to increase the level of integration without changing the basic premises. Advanced scheduling is then used to squeeze the most out of a fundamentally unchanged production system. But as the number

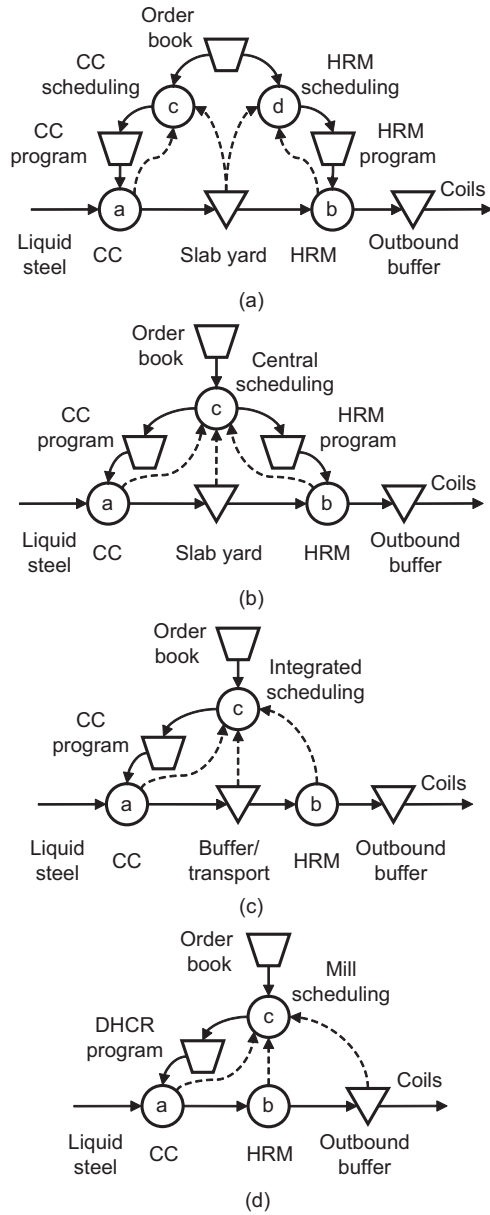


Figure 47: Operational modes for an integrated steel mini-mill: (a) decoupled operation, (b) loose integration, (c) close integration, and (d) unbuffered operation. From Paper ii [82].

of product variants and constraints on scheduling increase, the quality of an optimised schedule deteriorates quickly.

Arguably, development of a new scheduling method will not result in a redefined competitive frontier. Instead, it is an example of performance improvement relative to an existing competitive frontier.

The results of this thesis suggest that a main cause for friction and waste in production is lack of process flexibility. Poor flexibility makes decoupling and buffers necessary. On the contrary, two process steps can be said to be compliant when the downstream operation can process material that is delivered from the upstream process step without changing the job sequence. This may require development of improved support systems such as advanced scheduling, but the fundamental change is due to improved process flexibility that allows the producer to optimise its operations towards a different competitive frontier.

Setup time reduction is an improvement method that can be used to make adjacent processing steps more compliant. Incompliant processes cannot be integrated unless the process flexibility of some or all processes is improved. This limits what can be accomplished using e.g. lean production methods in a steel plant. As long as processing equipment remains inflexible, buffering is necessary and the amount of buffering that is needed increases with the number of product variants.

However, it is not always necessary to make large investments to open up a new competitive frontier. It is possible to define a new competitive environment through gradual evolution of production capabilities and the accumulated effect of numerous small incremental improvements. At the same time, daily problem solving may have unintended consequences as small “optimisations” often yield small reductions in process flexibility.

To conclude, existing improvement methods in the steel industry are focused on optimisation of existing technology, which means reduction of the gap to an existing competitive frontier. High-variety producers can gain a competitive advantage by moving to a new competitive frontier if they consciously focus on process flexibility improvements to raise production performance. Innovative, flexible, processing technology provides the opportunity for cost reduction as well as improved energy efficiency, thereby simultaneously improving productivity and reducing emissions to the environment.

7.6 CRITICAL REVIEW AND FUTURE RESEARCH

Before the validity of the results are discussed, it is of value to note that the contributions to scientific knowledge of this thesis fall in two distinct fields.

First, there is a contribution to knowledge on performance analysis in steel production. This includes development and analysis of models for the interaction between business strategy, capabilities and production system design. The scope of research is the steel industry, but it seems likely that some findings are valid for other industries as well.

Second, there is a contribution to research on strategy formation and links between strategic and operational capabilities. This thesis has suggested some ideas that can be potentially useful as foundations for future research in this field. This includes linking the development of capabilities to organisational learning, the concept of capability requirements analysis and the use of exploratory data analysis (EDA) in this process. There are also contributions within process cost modelling, including simulation-based DPCM.

This research has been cross-disciplinary, and as such, there are specific issues that must be dealt with. First, depth must by necessity be traded-off for breadth. This means, for example, that it has been possible to develop process and operations models to a certain level of detail only. Of course, there are always limits to what can be accomplished within a certain time and budget. However, this is even more evident within cross disciplinary research. There will be competing activities that must be carried out by the researcher and there will be less time to focus on each activity. This limits the depth of knowledge that the researcher can develop within each field. A cross-disciplinary researcher becomes an expert on the interaction between fields, rather than an expert on any particular field.

Are the results scientific, and can they be considered to be valid? These issues are discussed with respect to simulation modelling in Chapter 4 and in Paper i [79] but will be further elaborated here.

Validation issues can be discussed from different perspectives. There is the questions of validation of production models and interpretations of the simulation analysis. There is also the question of validity of the methodological framework: the five-step

framework and the strategy process model, capability assessment, and the role of capabilities and links between strategy and production operations.

The methodological framework is primarily based on literature studies and practical experiences. Some ideas were subjected to peer-review due to their inclusion in the published papers. Others remain untested. When is the five-step framework applicable? Should DPCM be used continuously to support learning and provide input to the strategy process? It is too early to say, and the future will show which of these ideas that will stand the test of time.

Other parts of this research are based on well tested empirical evidence. This is true in particular for individual process and operations models. However, there is also the issue of breadth versus depth, meaning that a process like reheating is based on a model that has been practical (and sufficient) for the purpose, rather than a model that is known to be more correct. In such a case, validation becomes an issue of judging whether the results are representative, and if a model behaves in a realistic way, rather than if the model is capable of replicating historical data.

The models of Chapter 5 deserve further attention. It would be valuable to do empirical studies to validate some of the more important models. For example, the production control model which is mainly based on literature studies and the author's personal communication. The second is the way that product variety is represented in the model. The third is the model for calculation of the fraction setup and sequence factor.

Altogether, it is clear that there is considerable potential for future research based on the propositions in this thesis. Models can be extended to include neighbouring process steps such as steel making, cold rolling, annealing and other processing. New process models can be added that account for energy consumption in more production steps. Focus for such a model can with little effort be shifted towards evaluation of environmental impact of production. There is also a need for validation of models and methods using empirical methods.

There is also plenty of potential for research on strategy formation and its links to operational capabilities in the steel industry. It would be interesting to evaluate the results of different operations improvement programs. Also, it would be interesting to study the links between product and production development.

Is it possible to conceive a method similar to design for assembly (DFA) for steel product development?

Practical implications of this research are, for example, as a basis for performance improvement and innovation since they make it possible to estimate the potential for productivity improvements and cost reduction as well as reductions in CO₂ emissions due to the introduction of new flexible processes.

The mould metallurgy technology for just-in-time alloying that is discussed in Paper vi [5] is an example of innovation that would be beneficial in many ways, both commercially and environmentally. The size and complexity of such a project is such that it could be beneficial to involve resources from the Swedish steel industry as well as universities and research institutes. A joint research programme could be initiated to develop and commercialise this technology.

To conclude, characterisation of steel production and its links to strategic and operational capabilities, is a field with many practical implications as well as interesting opportunities for future research. This thesis provides some starting points, and the author hopes that other researchers will be encouraged to follow.

Part II

APPENDICES

EQUATIONS FOR THE SLAB COOLING AND REHEATING MODEL

This appendix provides a brief summary of the assumptions behind the slab cooling and reheating models. Section A.1 discusses slab cooling, and estimation of the power supplied by the furnace burners. Section A.2 discusses how the variation of the furnace capacity with the charging temperature and how this is modelled.

A.1 FURNACE POWER

In order to estimate the reheating power the temperature of slabs that enter the furnace must be known.

Cooling rates for slabs vary widely for different geometries and boundary conditions. Boundary conditions include factors such as ambient temperature, air circulation, whether slabs are stacked in piles and where in a pile a slab is resting. However, a simplified cooling model was considered to be sufficient since dynamic process cost modelling (DPCM) uses an aggregated approach with production modelled as a continuous flow (t/h).

The surface temperature of slabs that were allowed to cool in the slab yard was measured with a pyrometer at different times after casting. For practical reasons the temperatures were measured in the centre of the narrow face of the slabs. A 2D-model of three stacked slabs was then implemented in STEELTEMP [42] and a simulation of the temperature evolution conducted and compared to the measured data. The relation between cooling time and temperature is shown in Figure 48.

The temperature of slabs upon charging into the furnace determines both the furnace power and the throughput capacity as discussed below.

A gas temperature of about 1000°C is maintained when the furnace is empty. The resulting idle power, P_0 , is individual for different furnaces but was found to be about 8 MW for a furnace at the Avesta plant. The furnace power in (MJ/h) can

be estimated if the required thermal input, h (MJ/t), and the furnace throughput, r (t/h), are known:

$$P = P_0 + \eta h \min(r_{\text{reheat}}, r_{\text{roll}}), \quad (\text{A.1})$$

where η is the current furnace efficiency. The effective production rate is the minimum of the current capacity of the furnace, r_{reheat} , and the capacity in the rolling operation, r_{roll} .

The furnace efficiency, η , depends on the hearth area coverage, which in turn depends on throughput. Hence, energy efficiency will also be a function of throughput. Figure 49 plots the efficiency of a furnace at the Avesta plant against throughput (t/h), together with an adapted model function.

In this case a throughput of 100 t/h yields an efficiency of 48%, which may be compared to an efficiency of 42% at 121 t/h as reported by Chen et al. [12]. The efficiency will vary between different furnaces depending on its size and design.

The amount of energy per tonne that must be transferred to the slab during reheating can be estimated from

$$h = \int_{t_1}^{T_2} c_p(T) dT. \quad (\text{A.2})$$

The temperature dependence of the specific heat [1] was approximated using an expression on the form $c_p = a + bT$. With this taken into account, the estimated heat loss for a slab that is

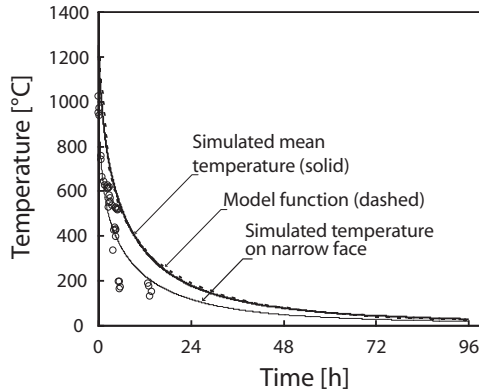


Figure 48: Slab temperature on narrow face and cross section average temperature for a slab with width 1.5 m and height 0.2 m.

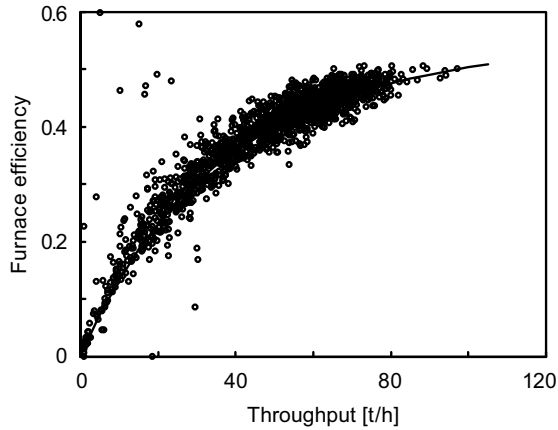


Figure 49: Furnace efficiency as function of production rate.

heated from 20°C to 1250°C becomes 26% higher than if constant specific heat is assumed.

With this inserted into Equation A.2, we get

$$h = a(T_2 - T_1) + \frac{b}{2} (T_2^2 - T_1^2). \tag{A.3}$$

The structure of the system dynamics reheating process model is seen in Figure 50. It is seen how the idle power, furnace efficiency and charging and discharging temperatures are used to estimate the current furnace power as discussed above. This model integrates with the main model as seen in Figure 33.

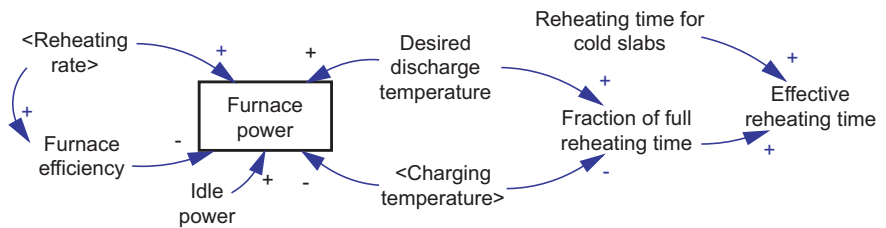


Figure 50: Model for estimation of reheating furnace power and throughput capacity.

A.2 FURNACE CAPACITY

The minimum time needed to reheat a slab depends on both the charging and discharging temperatures. When a cold slab is reheated, the heat spreads gradually towards the centre, causing an inhomogeneous temperature profile. Since the deformation resistance of the material is temperature dependent, the temperature must reach the target temperature throughout the material. The temperature distribution must be relatively homogeneous, so the slab is kept in the furnace until the temperature inhomogeneity is small enough not to affect the subsequent hot rolling process adversely by causing significant variations in material properties. This is known as soaking the metal, and the minimum required reheat time is called soaking time.

A numerical heat transfer model for the cross section of a slab was developed, and the minimum reheat time required to reach the target temperature of 1250°C as function of initial temperature determined. The amount of soaking was measured as the temperature difference between the coolest and the warmest part of the cross section. The criterion for the minimum reheat time was that the target temperature was reached with a maximum temperature inhomogeneity of 20°C within the work piece.

This model was a 2D finite difference scheme based on the alternating directions implicit (ADI) method [25]. The initial temperature was assumed to be homogeneous, and the heating rate throughout the cross section then followed from the boundary conditions. The temperature on the outer boundary of the cross section was given as function of the slab's position in the furnace (cf. Chen et al. [12]).

Figure 51 shows the simulated heating curve. An iterative procedure was used to find a suitable reheating time, depending on initial temperature, such that the temperature inhomogeneity, ΔT , between surface and centre of the cross section was less than 20°C .

This model was used to estimate the reheating time and throughput as function of the charging temperature. The relative reduction of reheating time with increasing initial temperature was found to be independent of the slab thickness. The required reheating time for any desired charging temperature can therefore be estimated according to Figure 52 if the reheating time for a cold slab is known.

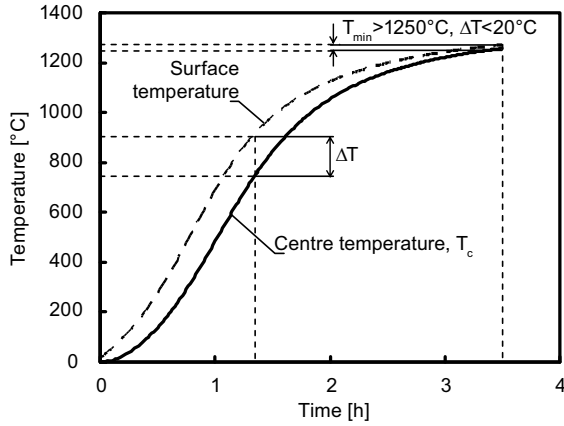


Figure 51: Predicted centre temperature, T_c , for simulated reheating.

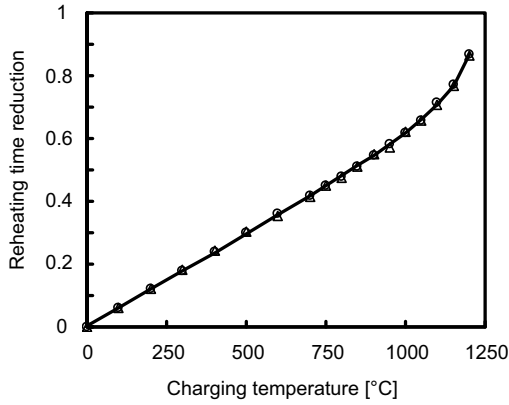


Figure 52: Relative reduction of reheating time compared to cold slabs.

The relative reduction of reheating time is $R_T = 1 - t_T/t_a$, where t_T is the reheating time and t_a the time to reheat a slab from ambient temperature.

The maximum throughput of the reheating furnace, $r_{T,max}$, for a given charging temperature can be written as

$$r_{T,max} = \frac{M}{t_{eff}} = \frac{M}{t_a(1 - R_T)}, \tag{A.4}$$

where t_{eff} is the effective reheating time and M is the volume capacity (tonnes) of the furnace. Substituting R_T yields the expression

$$r_{T,max} = \frac{M}{t_a} \left[1 - \left(1 - \frac{t_T}{t_a} \right) \right]^{-1}. \quad (A.5)$$

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INDEX

- annealing, 9, 100
- AOD, *see* converter
- assemble to order, 24
- ATO, *see* assemble to order
- automotive, 18

- backlog, 44, 46, 51, 52, 60, 69
 - adjustment, 46, 51
 - desired, 52
- balancing loop, 46, 60
- batch, 9–11, 24–26, 54, 59, 68,
 - 74, 76, 92
 - size, 25, 26, 54, 59, 68,
 - 74, 88, 92
- best practice, 95, 96
- black-box
 - model, 32
 - validation, 36
- brushing, 40
- buffer, 5, 6, 10, 16, 27, 28, 61,
 - 64, 72, 91, 95, 98
- buffering, 5, 16, 27, 95

- capabilities, 3, 4, 6, 7, 18–23,
 - 28–32, 38, 39, 42, 68,
 - 88, 90–93, 95, 96, 99,
 - 100
 - dynamic, 20
 - manufacturing, 4, 20, 22
 - operational, 3, 4, 7, 18,
 - 20–23, 28, 29, 42, 88,
 - 90–92, 99, 100
- capability, 3, 4, 19, 20, 27–32,
 - 38, 39, 42, 43, 93–95,
 - 99, 100
 - awareness, 30–32, 39, 93,
 - 94
 - gap, 30, 31, 39, 42, 93, 95
 - requirement, 4, 28, 32,
 - 42, 43, 93, 99
- casting rate, 11, 46, 47, 49
- CC, *see* continuous casting
- change rate, 46
- charge, 3, 6, 11, 12, 44, 47, 53,
 - 54, 57, 59, 60, 69, 71,
 - 74, 76, 78, 80, 85, 86,
 - 92
- charge weight, 59, 60, 69, 74,
 - 76, 78, 80, 85, 86
- charging rate, 63
- charging temperature, 6, 14,
 - 63, 64, 71, 76, 78, 80,
 - 82, 83, 85, 105, 107–
 - 109
- cluster, 55
- cold grinding, 12
- cold rolling, 9, 100
- communication, 89, 100
- competencies, 22
- competition, 3, 15, 21
- competitive
 - advantage, 17, 19
 - frontier, 7, 23, 41, 90, 95,
 - 96, 98
 - priority, 15, 86
- complexity, 3, 39, 89
- configuration, 32, 35, 39, 41,
 - 88
- continuous casting, 6, 7, 9,
 - 10, 24–26, 43, 44, 47,
 - 50, 55, 69, 72, 74, 76,
 - 78, 80, 82, 83, 85, 88,
 - 91, 92, 95, 96

- control mode, 24, 25, 44, 100
- control system, 12, 25
- converter, 9, 10, 96
 - AOD, 9, 10
 - Bessemer, 96
- cooling, 11, 12, 28, 44, 61, 64, 72, 95, 105
- cooling zones, 11
- corporate strategy, 17, 18
- cost, 3–7, 15, 21, 23, 24, 27, 29, 31, 32, 37–39, 42, 65, 69, 71, 72, 74, 76, 78, 80, 82, 83, 85–92, 96, 99, 101
 - reheating, 74, 76, 80, 88
 - setup, 27
- cost model, 6, 29, 32, 37, 38, 42, 99
- cost penalty, 27, 85, 96
- creativity, 20
- cross-disciplinary, 89, 93, 99
- customer
 - order, 24–26, 44, 50, 52, 61, 71, 89, 91
 - service, 25, 60
- database, 36, 40, 41
- decision making, 29
- decoupled, 6, 16, 24, 26, 43, 83, 96
- delivery delay, 52, 60, 68, 69, 71, 86, 88
- demand, 3, 15, 25, 44, 47, 51, 53, 54, 86
- dependability, 21, 85, 86
- descaling, 12
- design pattern, 90
- differentiation, 3, 21, 22
- downtime, 64
- drive torque, 15
- dynamic fit, 21, 28, 95
- EAF, *see* electric arc furnace
- economic niche, 21
- EDA, *see* exploratory data analysis
- efficient frontier, 23
- electric arc furnace, 9, 10
- emergent, 17, 19, 20, 28, 31, 88, 92, 93
- energy, 6, 15, 67, 100, 106
- equilibrium, 22, 24, 54, 60
- equipment, 4, 15, 96
- Ericsson, 20
- event, 4, 13, 31, 33, 35, 61, 62, 64, 93
- evolution, 15, 19–21, 31, 93, 105
- evolutionary, 19–21, 31
 - learning, 20
- exploratory data analysis, 6, 38, 40, 99
- five-step framework, 6, 32, 34, 39, 99, 100
- flexibility, 4–7, 15, 21–24, 27, 28, 42, 65–68, 71, 80, 82, 85–92, 96, 98
- flow, 4, 10, 32, 35, 44, 47, 50, 54, 64, 67, 68, 88, 105
- forecasting, 44
- fraction setup, 6, 47, 57, 100
- framework, 6, 7, 16, 17, 23, 29, 32–34, 39, 42, 88, 89, 93, 99, 100
- furnace, 9, 12–15, 44, 63, 76, 78, 83, 85, 105–110
 - capacity, 105
 - control, 63
 - power, 105, 107
 - utilisation, 15, 63, 76, 78, 83, 85

- future research, 87, 90, 99,
 100
 goals, 7, 17, 40, 41
 grain growth, 95
 grinding, 12, 14, 65

 heat transfer, 95, 108
 high-variety, 3, 85, 87, 91, 96
 hot rolling, 4-6, 9, 11, 24, 26,
 43, 44, 53, 55, 57, 61,
 64, 65, 67-69, 71, 72,
 74, 76, 80, 82, 83, 85,
 91, 95, 96, 108
 HRM, *see* hot rolling

 illumination, 29
 implementation, 6, 18, 20, 36,
 37, 49, 62, 86
 improvement, 6, 16, 20, 23,
 28-30, 32, 40, 67, 68,
 78, 85, 87-89, 92-96,
 98, 100, 101
 improvement trajectory, 6, 30,
 40, 94
 incubation, 29
 ingot casting, 28
 initial temperature, 14, 108
 innovation, 7, 21, 23, 96, 101
 inventory, 4, 6, 25, 50, 51, 53,
 64, 69, 71, 72, 74, 76,
 78, 80, 86, 88

 JIT, *see* just-in-time
 just-in-time, 3, 4, 7, 101

 knowledge, 4, 28-31, 91, 93,
 96, 99

 leadtime, 16, 55
 lean production, 4, 6, 16

 learning, 7, 20, 24, 29, 31, 37,
 40, 42, 87-89, 93, 99,
 100
 levelling, 47, 49
 low turnover, 25, 53, 71
 low-variety, 91

 make to order, 24-26, 52
 make to stock, 24-26
 management, 4, 15, 17, 20,
 30, 93
 manufacturing, 3, 4, 6, 15-18,
 20, 22, 28, 37, 38, 55
 market, 3, 7, 15, 17, 18, 21, 22,
 28, 29, 39, 42, 43, 88,
 90, 93, 95
 market requirements, 21, 28,
 93, 95
 melting, 9, 11, 12
 meltshop, 10, 24, 26, 28, 43,
 47, 50, 59, 83, 96
 mental models, 20, 31
 metallurgy, 7, 92, 101
 mill stand, 95
 mini-mill, 9, 10, 96, 97
 model
 economic, 31
 financial, 37, 38
 operations, 37, 99, 100
 process, 37, 66, 89, 93,
 100, 107
 testing, 6, 34, 35, 37, 89
 mould, 7, 11, 92, 101
 MTO, *see* make to order
 MTS, *see* make to stock

 niche, 3, 4, 7, 15, 21-23, 90
 nucleation, 95

 operational mode, 24, 89
 operations, 4, 6, 26, 28, 32,
 37, 38, 40, 47, 62, 64,

- 67, 88, 89, 95, 98–100
- optimisation, 96
- order
 - coupling, 24, 26, 44, 52, 64, 91
 - frequency, 26, 49, 55, 83
 - fulfilment, 51, 52, 61
 - rate, 27, 44, 52–54, 60, 68, 74
 - volume, 15, 26
- organisation, 4, 7, 15, 17, 19–22, 27–31, 37, 42, 44, 87, 92, 93, 99
- organisational learning, 7, 29, 31, 87, 93, 99
- overproduction, 59
- oxide, 12
 - scale, 12
- pacing, 50
- performance, 4–7, 15, 16, 18, 23, 24, 31, 32, 35, 38–42, 54, 60, 66–68, 71, 80, 82, 85, 87–89, 95, 98, 99, 101
- phase transformation, 95
- pickling, 9
- planning, 17–20, 35, 39, 89
- policy structure diagram, 44, 89
- precipitation, 95
- preparation, 29
- process flexibility, 4–7, 23, 24, 28, 42, 65–68, 71, 80, 82, 85–88, 91, 92, 96, 98
- process step, 4, 5, 15, 62, 89, 92, 95, 98, 100
- process technology, 5, 95, 96
- processing time, 12, 60, 78
- product
 - differentiation, 22
 - group, 44, 46, 47, 49, 50, 53–55, 58–60, 64, 68
 - high-volume, 3, 49, 64, 83
 - intermediate, 9, 51
 - low-volume, 26, 49, 58, 60, 64, 83
 - range, 27, 31, 39, 44, 59, 66–68, 72, 78, 82, 83, 90, 91, 96
 - variety, 3–7, 15, 23–26, 28, 32, 42, 44, 54, 57, 67–69, 71, 72, 74, 76, 78, 80, 82, 85, 87, 88, 91, 93, 96, 100
- production
 - capacity, 57, 60, 68, 69, 74, 78, 80
 - control, 44, 46, 49, 100
 - order, 25, 52
 - schedule, 12, 26
 - start rate, 46, 50–52
 - system, 3, 4, 24, 26, 39, 42, 43, 66, 89, 91, 95, 96, 99
- productivity, 4, 31, 39, 71, 101
- program duration, 59, 83
- pseudo composite product, 55, 68, 88
- pull
 - production, 26
- push
 - production, 26
- qualitative, 35, 37, 40
- quality, 3, 11, 12, 21, 22, 31, 86, 92, 93, 98
- range fraction, 58
- recrystallisation, 95

- refining, 10–12
- reheating, 6, 12–15, 44, 61, 63, 64, 68, 69, 74, 76, 78, 82, 83, 85, 95, 100, 105–110
 - cost, 69, 76, 78, 82, 83, 85
 - furnace, 12, 14, 44, 63, 76, 109
 - time, 14, 63, 95, 108–110
- requirements, 3, 4, 21, 24, 28, 29, 31, 32, 37, 42, 43, 87, 88, 92, 93, 95, 96, 99
- rescheduling, 62
- research, 3–7, 17, 18, 22, 35, 40, 87, 89, 90, 99–101
 - activities, 5
 - question, 5, 7, 87
- resource, 4, 17–19, 21, 22, 31, 37–39, 66, 87, 88, 92
- right-sized, 26
- roll
 - change, 44, 64, 65
 - force, 15
 - grinding, 14, 65
 - wear, 6, 44, 65
- rolled length, 15, 65
- roller table, 11
- rolling speed, 15
- roughing mill, 13
- SCC, *see* steelmaking—continuous casting
- schedule fraction, 47, 49, 50
- scheduling, 4–6, 11, 43, 44, 47, 49, 50, 55, 57, 59, 61, 62, 67, 68, 74, 83, 91, 95, 96, 98
 - dynamic, 62
 - methods, 4, 5, 96
 - period, 6, 47, 49, 59, 61, 62, 83
 - policies, 6, 49, 57
- scrap, 9, 10, 14, 96
- SD, *see* system dynamics
- sensitivity simulation, 40, 54
- sequence factor, 12, 47, 54, 57–59, 85, 100
- setup, 6, 11, 12, 14, 23, 27, 44, 47, 57, 59, 64, 67–69, 71, 72, 74, 76, 78, 80, 82, 85, 86, 91, 92, 95, 100
- shading, 40
- Shigeo Shingo, 3, 23, 91
- simulation, 4, 5, 7, 29, 32–36, 39, 40, 54, 67, 89, 99, 105
- slab
 - cooling, 61, 72, 105
 - geometry, 13, 28
 - production, 24, 43, 44, 80, 91
 - width, 26, 49, 55
 - yard, 9, 11, 24, 26, 43, 44, 50, 64, 83, 96, 105
- slabs, 9, 11, 12, 14, 25, 26, 50–53, 55, 57, 61–64, 72, 74, 78, 82, 83, 85, 88, 91, 105
 - ordered, 50–53, 61, 74, 78, 83, 85
 - unordered, 50–53, 74, 78, 85
- SMED, 3, 4, 23, 28, 91, 92
- soaking pit, 57
- software, 40, 90
- specialisation, 15
- speed, 15, 40
- steckel mill, 13
- steel

- carbon, 12
- grade, 12, 26, 28, 57
- industry, 21, 89, 90, 99, 100
- producer, 3–5, 7, 15, 22, 23, 87, 90, 94, 95
- production, 3–5, 7, 9, 12, 23, 25, 26, 28, 42, 43, 55, 66, 87, 89, 92, 99
- special, 3
- stainless, 9, 12, 26, 55, 92
- steelmaking, 7, 9, 68, 80, 92
- steelmaking—continuous casting, 10, 25, 69, 72, 74, 76, 78, 80, 82, 85, 88
- strategy
 - business, 4, 17, 30, 31, 93, 99
 - emergent, 20, 88, 93
 - functional, 17, 20
 - generic, 21
 - intended, 20, 22
 - market, 3, 15, 42
 - process, 5–7, 19–22, 30, 37, 38, 87, 88, 93, 100
 - realised, 29, 92
- strip, 3, 9, 12–14, 26, 28, 52, 61, 67, 91
- supply rate, 64
- surface defects, 11, 12, 14
- synthesis, 7, 20
- system dynamics, 6, 29, 31, 32, 34–37, 39, 66, 88, 89, 107
- system-of-systems, 31
- systems engineering, 31
- Taiichi Ohno, 4
- technology, 5, 7, 20, 23, 28, 31, 32, 38, 89, 95, 96, 101
- temperature, 6, 12–14, 63–65, 71, 72, 76, 78, 80, 82, 83, 85, 105–109
- testing, 6, 33–35, 37, 89
- theory, 32, 34
- Toyota, 4, 18, 20, 23
- Toyota production system, 4, 20
- transfer bar, 13
- triangulation, 36
- tundish, 10
- turnover, 11, 25, 47, 53, 57, 59, 62, 71
- uncertainty, 27
- utilisation, 14, 15, 55, 63, 69, 72, 76, 78, 80, 82, 83, 85
- validation, 35–37, 99, 100
- validity, 36, 37, 99
- value-added, 3, 5, 87, 92
- variability, 28
- verification, 29, 36
- volume flexibility, 86
- volume fraction, 58, 59, 83
- waste, 95, 98
- wear mark, 65
- white-box
 - model, 31, 32
 - validation, 36
- WIP, *see* work-in-process
- WIP-cap, 25, 26
- work rolls, 14, 65, 67
- work-in-process, 6, 16, 25, 26, 43, 46, 50, 61, 62, 64, 67, 72, 85, 86
- workpiece, 9, 14, 28, 108

Part III

APPENDED PAPERS