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Exploring improvement trajectories with dynamic process cost modelling: A case from the steel industry

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Improvement trajectories are sequential managed chains of improvement initiatives required to handle changes in competition and market. This paper presents a five-step framework, based on dynamic process cost modelling, which was developed during a four-year research project at a major stainless steel producer, to support the selection of an improvement trajectory based on strategic requirements to combine high product diversity with cost reduction. The framework aims to develop insight into what manufacturing capabilities are required to reach the strategic goals by combining system dynamics simulation with process cost modelling and visual exploratory data analysis in an iterative modelling procedure. The applicability of the five-step framework is demonstrated through a case study from the steel industry, in which a goal driven analysis is used to assess process requirements based on performance and market considerations.

Keywords: Cost analysis; Manufacturing strategy; Simulation; Process industry; System Dynamics; Exploratory data analysis

1. Introduction

Successful companies continuously develop new capabilities that allow them to handle threats and opportunities as they arise. Hayes and Pisano (1996) states that the new role of strategy is "to make possible dynamic tradeoffs through the selection, development and exploitation of superior capabilities". They argue that firms that manage to harness various improvement programs in the service of a broader manufacturing strategy can turn manufacturing into a competitive advantage. A central issue is to decide what capabilities to develop in order to transform manufacturing into a source of sustainable competitive advantage.

Ohno (1988) considered most production initiatives to be cost-driven, stating that "all change should boil down to cost reduction". However, this does not in itself need to imply a narrow product range. Instead, it is necessary to properly assess the manufacturing flexibility requirements to support the contemplated range of product volumes (Berry and Cooper, 1999). Development of new capabilities along multiple dimensions can allow simultaneous improvement of cost and flexibility performance. Ohno's statement should therefore be understood as cost reduction compared to alternative configurations that satisfy the requirements of the chosen business strategy.

An improvement trajectory implies a managed sequence of initiatives to raise performance (Da Silveira, 2002). Central ideas within the theory of improvement trajectories are path dependence and dynamic capabilities. Dynamic capabilities contrast with ordinary capabilities

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in that they are concerned with change (Winter, 2003). Since dynamic capabilities are cumulative (Ferdows and De Meyer, 1990), the order in which strategic initiatives are applied matters. This is elaborated by Flynn and Flynn (2004), who propose a sandcone model that links strategic initiatives to the sequential development of cumulative capabilities.

Performance measurement is an important instrument in a firm's internal process of strategy making (Leong et al., 1990). However, it is necessary to differentiate between manufacturing capabilities and manufacturing outcomes. Cost is a manufacturing outcome, flexibility is a manufacturing capability (Swink and Hegarty, 1998). Hence, assessment of investments in new manufacturing technology must be approached from both an engineering and financial point of view (Busch, 1994; Field et al., 2007; Szekely, 1996).

The term *capability awareness* is proposed to denote 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. Development of routines that aim to raise the level of capability awareness addresses the issue of developing a "capability for capability building" (Fujimoto, 1999), to guide the selection of future improvement initiatives by providing better opportunistic learning capabilities. Process-based cost models can play an important role in this process.

The present paper discusses the potential to support the strategy process with dynamic process cost modelling. A five-step framework is proposed for assessment of current and future production capability requirements. A case study from the steel industry illustrates how the five-step framework can aid the development of capability awareness through an explorative search for improvement trajectories that support the goals of the chosen business strategy.

2. State of the art

2.1. Process cost modelling

The significance of cost estimations is emphasised by Field et al. (2007), who argue that process based production cost models are vital to avoid that the engineers' technical measures are set aside by firm management "in favour of more poorly supported, but wholly familiar, cost metrics devised by those with only a passing familiarity with the technical issues at the real heart of the issue" (Field et al., 2007). The use of cost models that fail to account for the effects of new process technology or operating practice from an engineering perspective, may in fact lead the firm towards an unintended change trajectory that makes it difficult or even impossible to reach the desired goals.

According to Szekely et al. (1996), neither physical engineering models, nor traditional financial cost models are particularly well suited for the task of guiding technology strategy and business development. Instead, building better, more robust, cost models requires the incorporation of physical modelling principles, while building better, more useful, physical models requires that they address pertinent business issues such as cost (Szekely, 1996).

Technical cost modelling (TCM) is an extension of conventional process modelling with emphasis on capturing the cost implications of material selection, process variables and changing economic scenarios (Arnold, 1989; Kendall et al., 1998; Park and Simpson, 2005). TCM is designed to follow the logical progression of process flow. Busch (1994) identifies eight cost elements that typically suffice to describe most processes:

- Materials
- Labour

- Energy
- Capital equipment
- Tooling
- Building space
- Maintenance
- Time value of money

For each cost element, simple relations, or "identities", can be defined. Key variables within cost identities are then replaced with predictive equations derived from first principle theories and/or from the analysis of commercial practice. It is the linkage of cost identities to process parameters that differentiate TCM from standard cost estimation templates (Busch, 1994).

Wang et al. (2000) found that current cost model development processes did not possess the efficiency or responsiveness needed to cope with new materials and manufacturing processes, as well as with an increasing number of product variants. It was suggested that neural networks could help to identify cost drivers, simplify model development, and allow more variables to be included in cost models.

Park and Simpson (2005) suggested a three-stage production cost estimation framework which draws on TCM. Required production activities are identified in an initial resource allocation stage. The second stage is cost estimation, which involves modelling of resource consumption rates using the chosen product design variables. Finally, in the analysis stage, product design alternatives are assessed by varying design parameters.

According to Field et al. (2007), cost can be identified as an emergent property, which depends on the context within which products are designed and manufactured. They propose a three-layered approach to cost modelling, 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; and
3. a **financial model**, in which resource requirements are converted to economic costs.

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" (Field et al., 2007). This need is evident for cost modelling in the process industry. For example, a steel mill may produce a large number of product variants that differ in chemical composition, casting geometry and rolling temperature. However, since all variants undergo the same processing activities, it is primarily the dynamic behaviour of the manufacturing system that determines cost.

The need to include temporal dynamics is also noted by Kendall et al. (1998), who found that TCM tends to underestimate manufacturing costs since "the traditional TCM approach assumes that each step in the manufacturing process operates independently from one another for a temporal standpoint of part flow" (Kendall et al., 1998). This is due to the difficulty of modelling a dynamic course of events within a spreadsheet environment. Indeed, cost models have combined TCM with system dynamics (Tucci et al., 1994), and with discrete event simulation (Kendall et al., 1998), in order to capture dynamic effects that the traditional TCM method failed to account for.

2.2. System dynamics

System dynamics is a generic modelling and simulation methodology with its roots in control theory (Ortega and Lin, 2004). The system dynamics methodology has developed from the

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pioneering work of Forrester (Forrester, 1961), who used computer based simulation to increase the understanding of dynamic behaviour in industrial supply chains (Fisher, 2005; Forrester, 2007; Ortega and Lin, 2004).

System dynamics is based on continuous simulation. Hence, causation is not expressed in terms of events, but as effects, or influence, between variables. A model consists of a combination of differential equations and causal loop diagrams that show causal relations between model parameters using text labels and directed arrows. The model is solved numerically using e.g. Euler integration or Runge-Kutta methods (Sterman, 2000).

Discrete event models differ from system dynamics models in that they concern instantaneous change of state (Law and Kelton, 2000). Event based modelling can be introduced in system dynamics models through the use of step functions and pulse trains. It is sometimes useful to use mixed continuous and discrete event modelling.

System dynamics uses an analogy where generic systems are modelled as stocks and flows (Sterman, 2000), which allows a system to be modelled in terms of high-level variables such as throughput rates and inventory levels. Reusability and rapid model development are characteristics of system dynamics modelling (Tesfamariam and Lindberg, 2005).

Applications of system dynamics are found in diverse fields of industrial research. Examples include inventory management, demand amplification, supply chain reengineering and management of international supply chains (Angerhofer and Angelides, 2000), mining and exploration (O'Regan and Moles, 2006), production systems engineering (Stamboulis et al., 2002) and manufacturing strategy and technology evaluation (Lyneis, 1999; Wolstenholme, 2003).

System dynamics simulation can be combined with Monte Carlo sensitivity simulation, a process that can be automated in order to conduct a large number of replications. A difficulty that is often encountered is the large amounts of data that results from sensitivity simulations. However, evaluation of sensitivity simulation results can be simplified through the use of visual exploratory data analysis as discussed in the following section.

2.3. Visual explorative data analysis

Exploratory data analysis (EDA) was introduced by Tukey (1977) as a method to support hypothesis formulation. It differs from confirmatory data analysis, which is mainly used to verify hypotheses after they have been formulated, in that the primary aim is to discover interesting features in the data (Cook and Swayne, 2007). During the last twenty years, development of specialised software changed the nature of graphical plots from formerly being a final product to now being an analysis tool where data views can be modified and adapted interactively on the computer screen (Wilhelm, 2005).

Linked views give graphical methods the capability of multivariate data analysis. A database is visualized simultaneously in different views, and changes and selections made in one plot are immediately reflected to all other connected plots (Wilhelm, 2005). This technique is known as *brushing*. The brushing operation immediately reveals how a region in one graph maps to different views of the same data. Nodes and edges in the data can be highlighted, labelled or painted in order to explore the distribution of values in the graph (Swayne et al., 2003).

Plots produced during this process are usually of a temporary nature, since new views are produced rapidly in search of clusters or interesting patterns. Data visualisation software typically supports linked views with histograms, scatterplots and parallel coordinate plots (Inselberg and Dimsdale, 1990). Some have features to display random sequences of projections in order to simplify the search for structures in high-dimensional space. The search for interesting views can be guided by an optimisation algorithm (Cook and Swayne, 2007).

Most literature on system dynamics is concerned with horizontal integration across supply chains. However, Ortega and Lin (2004) identified the need for an uniform generic modelling framework that is capable of integrating control theory based models vertically (within plants) and horizontally (across factories). A complication is the lack of analytical support, which is a problem of simulation based research in general (Ortega and Lin, 2004). The five-step framework proposed in this paper, with its emphasis on sensitivity simulation and explorative data analysis, targets these issues.

3. Proposed framework

The following section presents a five-step framework, based on dynamic process cost modelling, that aims to aid the development of capability awareness. The proposed framework consists of five steps (Figure 1), 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 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 analysis. 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.

(Figure 1)

The system dynamics paradigm emphasises continuous testing of models, which is particularly important in situations where historical data is unavailable or difficult to obtain (Sterman, 2002). The framework does not include validation as a separate activity. Rather, as seen in Figure 1, it is integrated in all steps of the framework.

Figure 1 emphasises the iterative nature of the framework. The cost model is gradually refined as process models are developed and linked with operations models. As the model matures, new insights can lead to a revised problem statement, 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.

During later stages, as the model reaches a state where it can be assumed to properly reflect the characteristics of the production system, the focus of exploratory data analysis shifts towards a search for improvement trajectories.

4. Case study from the steel industry

This section presents a case study where the five-step framework is used to assess improvement potential in an integrated mill for production of stainless steel strip.

The case study is based on a four year study, from 2004 to 2007, at a major stainless steel producer. During this time, the author had the role of embedded researcher within the process development group at the hot rolling mill.

4.1. The production environment

The plant, shown schematically in Figure 2, is representative for many integrated steel mills around the world. Liquid steel is produced from melting and refining of scrap. The metal is cast into workpieces (called *slabs*) of approximately 25 tons each through continuous casting (CC). Slabs are then hot rolled to strip in a hot rolling mill (HRM).

(Figure 2)

Hot rolling is strictly in response to customer orders, but since customers often order less than 100 tons, which is the minimum batch size of the meltshop, an inventory of excess slabs is kept in anticipation of future sales. Transfer times for slabs from casting to rolling are in the order of a few days for ordered slabs, while excess slabs may remain in the slab yard for weeks or months.

Before hot rolling, slabs are reheated to about 1250°C. This is where the potential for energy reduction is most evident since shorter transfer times yields a higher charging temperature. So-called hot-charging, defined as continuous operation at more than 400°C charging temperature (Tang et al., 2001), is an attractive option to reduce energy consumption. However, like many others (Beck, 2000), the plant has had difficulties to achieve the required reductions of work in process (WIP) and transfer times.

The product range is highly diversified. Production data from a period of six months showed that 7% of the product variants represented 50% of the produced volume (Figure 3). Products can be classified as either high-volume standard grades or low-volume special grades. Additionally, it was possible to differentiate products as either narrow or wide. Four product groups were thus identified, classified by turnover and width.

(Figure 3)

Management recognises that the difficulties to implement hot charging are caused by high variability due to the diversified product range, and that existing production equipment may not be optimally designed to handle this variation. Product range was therefore a key design variable in the case study. The question is what capabilities to develop in order to follow an improvement trajectory towards low-cost high diversity production.

4.2. Step 1: Problem identification

It was clear that energy consumption in the slab reheating furnaces was a key contributing factor to production cost. Energy consumption in the furnaces depend on many factors, e.g. furnace throughput rate (Chen et al., 2005), which is in turn influenced by other factors that are normally not regarded to belong to the furnace subsystem. Hence, the performance of the slab reheating process depends on work practice (operations) as well as choice of equipment (processes).

Initially, key factors were identified and a conceptual system dynamics model was produced during a project that involved members from the project engineering, process development and logistics functions in the rolling mill. The model was based on high level assumptions on how operations and manufacturing processes influence each other. Despite the crudeness of this model, it provided valuable insights that guided the further analysis.

The development of the first model was followed by the development of improved cooling and reheating models. This involved numerical simulation of the cooling and reheating processes. The cooling model was validated against temperature measurements on slabs in the slab yard, while the reheating model was validated against data from the reheating furnace control system. Equations were adapted to the validated models and integrated in the cost model.

In retrospect, the problem identification phase can in itself be seen as an iterative procedure that contains all stages of Figure 1. Development of conceptual models involved aspects of both process and operations modelling. New insights resulted in the formulation of new hypotheses, and completed iterations yield input to the problem identification stage of later iterations.

4.3. Steps 2 and 3: Process and operations modelling

As mentioned initially in Section 4, the influence of product diversification was a key issue. The full range of products was aggregated into four groups, and implemented in the model with subscripted variables to create four parallel flows.

The structure of the model in its later stages of development is shown in Figure 4. It includes production scheduling, product range and volumes, energy consumption and throughput. It also includes setups due to work roll changes and caster restarts. Newly cast slabs are transferred to the slab yard before they are charged into the reheating furnace. They are then reheated to rolling temperature, discharged from the furnace, and processed in the rolling mill.

(Figure 4)

Figure 5 shows how slabs are first given the status of unordered slabs. The lead time calculation for each group is conceived to preserve the mean customer order frequencies for product groups as discussed in Section 4.1.

Ordered slabs that have been scheduled on the rolling mill are transferred to a reheating buffer, linking Figure 5 to Figure 6, from where they are charged into the reheating furnace.

(Figure 5)

Discrete event modelling techniques was used to model production scheduling, since:

- scheduling operations occur infrequently in comparison to the time resolution of other processes in the model, and
- the influence of scheduling on aggregated production flow was unclear.

It is assumed that material is perfectly blended in the slab yard. The average age of material in stock, *buffer age* in Figure 5, is then calculated for each product group.

Figure 6 shows the furnace model with reheating modelled as a two stage process. Cold slabs enter the reheating stage and undergo a gradual change of state to become reheated slabs. The transformation is modelled as a delay, where the transfer rate is influenced by a number of environmental factors as seen in the figure.

(Figure 6)

The final model is the result of an evolutionary development where many, often more complex, intermediate solutions have been rejected. It was sometimes necessary to conduct detailed analyses in order to establish how variables influence each other. For example, a 2D finite difference (FD) model was used to estimate the charging temperature. The FD model was tested through pyrometer measurements on real slabs in the slab yard in front the hot strip mill.

Another 2D FD model was also used to predict the reheating time as function of charging temperature. Simple mathematical expressions were then fit to the simulated cooling and heating curves and inserted into the system dynamics model.

Figure 7 shows an example of a curve produced during validation of the reheating model. Charging and discharging rates from 48 h production was taken from the furnace control system in the rolling mill and supplied to the model. A time series of actual reheating power was then plotted together with the simulation output as shown in Figure 7. Considering the simplicity of the model, the comparison shows a reasonable agreement between simulation results and measured data.

(Figure 7)

Capital, labour and reheating cost rates were integrated over time to estimate the margin cost of each resource. Each cost component is a product of a resource price and its cost driver. Hence, the reheating cost was calculated from the energy price, multiplied by the furnace power (cf. Figure 7). The energy price was in turn based on the price of propane gas and the heat content of the gas.

4.4. Step 4: Sensitivity simulation

Once the model has reached a state where it executes properly, it is subjected to Monte Carlo sensitivity simulation. Several parameters are varied simultaneously according to random uniform distributions within chosen ranges. The values of key parameters, such as the different cost components, WIP, furnace utilisation and mean charging temperature, are then exported to a data table.

As discussed below, specialised EDA software is then used to view and evaluate the results.

4.5. Step 5: Exploring sensitivity data

The sensitivity simulation results were screened visually with the aid of linked plots using visual exploratory data analysis software. The sensitivity simulation results were pruned to remove branches that represent unfavourable configurations with low production capacity and high cost (Figure 8). A plot of mean reheating cost against mean capital cost (Figure 8a) shows two branches that extrude from the main cluster of points. One is characterised by extreme reheating costs and the other by extreme inventory costs. These branches were brushed to distinguish them from the main cluster.

(Figure 8)

A plot of total mean cost against total production volume (Figure 8b), shows how the brushed regions stand out with low to intermediate production volumes and high cost.

Plotting production capacity against furnace utilisation (Figure 8c) shows that low furnace utilisation is the main cause of high reheating costs. Contrary, high inventory costs are caused by over-utilisation of the furnace, turning reheating into a bottleneck.

Figure 8d shows that, in general, high mean reheat costs (Figure 8a) correspond to low charge weights and long setups in the caster. The result is low production capacity in the caster, which may cause poor utilisation in the reheating furnace if there is a capacity imbalance. At the same time, high inventory costs are associated with under-capacity in the reheating furnace. The rolling mill thus becomes a bottleneck, causing in-process slabs to stock up in the slab yard.

Once unfavourable configurations representing apparent capacity imbalance have been removed, the opportunities to reach the strategic goals by following a planned improvement trajectory can be investigated. This is done by brushing a desired future cost and product range region, and exploring which mill configurations yield the desired results.

Figure 9 illustrates how design parameters can be identified based on prior brushing of target regions in linked data plots. The figure shows a two-step trajectory towards increased product range with maintained or reduced cost.

(Figure 9)

Starting from Figure 9a, which shows the remaining data points when the high-cost branches seen in Figure 8 have been removed:

- A region corresponding to the current configuration and product range is brushed.
- A second region, representing the first step towards lower cost and increased diversification, is brushed with differing colour and symbol.
- A third region, representing further cost reduction and increased range, is brushed.

All remaining points except those that belong to the desired future configurations are then hidden (Figure 9b).

Figure 9c shows that, despite a significant spread, there is a trend that reduced mean cost is linked to increased production volumes. This is sometimes satisfactory, but if the firm's strategic goal is to maintain its current market share, cost may have to be reduced in absolute numbers instead.

A plot of setup times in the caster against charge weight (Figure 9d), shows that reduced setup times in the caster are required. In order to evaluate the effects of the charge weight, configurations with charge weights below the current 100 tons are brushed to distinguish them from higher charge weights as shown in Figure 10.

(Figure 10)

Figure 10a confirms that increased production volumes on average yield lower mean costs. However, this figure also shows that reduced costs can be accomplished without, or with little, volume increase if the charge weight is reduced. Increased charge weight typically increases the production capacity for a given product range (Figure 10b), but it must be accomplished by setup time reduction (Figure 10c).

Setup time reductions increase the production capacity and, as expected, there is also a correlation with cost (Figure 10d). However, in order to accomplish real cost reductions, it is necessary to also reduce the charge weight. The elimination of excess slabs results in reduced WIP and inventory costs in the first step. Charging temperatures can then be increased in the second step, with lower reheating costs as a result (Figure 10e). Production capacity can be maintained, or even increased, since setup times are reduced.

4.6. Identifying an improvement trajectory

Based on the results of the sensitivity analysis, a two-step program to reduce cost and increase diversification was outlined. Each step involves a number of initiatives to develop new manufacturing technologies and operational practice. The suggested changes, based on the analysis in Section 4.5, are summarised in Table 1.

(Table 1)

New sensitivity simulations were conducted in 250 replications, with the design variables varied according to Table 1. The output was compiled in a parallel coordinate plot (Figure 11), which shows how configurations B and C permit increasing production volumes and reduced cost despite increasing product range.

(Figure 11)

Table 1 specifies long-term targets for improvement in terms of generic capabilities of the manufacturing system. These new capabilities can only be the result of long-term organisational commitment. Thus, the organisational capabilities needed to implement the suggested change must be developed first.

Table 2 lists development of setup time reduction, innovative scheduling policies and new process technology as key organisational capabilities that must be developed before the desired improvement trajectory can be realised.

(Table 2)

Reduction of setup times in the hot rolling mill facilitates more frequent roll changes, thereby shortening the scheduling horizon. Transfer times can then be reduced, which increases the mean charging temperature. Dynamic updating of schedules ensures that slabs reach the rolling mill with as little delay as possible. The responsibility for production scheduling can be decentralised and new scheduling policies introduced.

Reduced charge weights may involve making larger batches of a few base grades, while alloying to final composition is delayed. This can be accomplished through ladle metallurgy, or even though just-in-time alloying using techniques such as tundish metallurgy or mould metallurgy (Bentell et al., 2008).

5. Discussion

The choices of market segment and product range are key decisions for any firm competing on an international or global market. According to the capability based view of the firm, manufacturing cost is limited by the existence of competitive frontiers, which are given by current technological and operational practice. This current 'best practice' defines the competitive frontier that limits the possibilities to obtain competitive advantages in relation to other firms (Hayes and Pisano, 1996). Since most firms in a particular industry use similar equipment and organisation, competitive advantage is based on optimal utilisation of resources such that unit cost is minimised in relation to firms competing on the same frontier. This is sometimes interpreted as if a wider product range must come at the expense of increased unit cost. However, development of new production capabilities can increase the level of process flexibility such that production cost decrease despite increased product range.

The presented framework emphasise the role of model testing. It is argued that learning is primarily taking place within the testing loop. The existence of transitory stages in modelling is a natural part of scientific inquiry (Popper, 1959). The model matures for each testing loop, which means rejection of some model features while others are strengthened or introduced. In this way, an awareness of what manufacturing features and capabilities that are needed to support the strategic goals can develop gradually.

The use of system dynamics allows production to be interpreted in terms of flows instead of individual objects that move through the plant. Hence, it was easy to adopt a high level perspective, where aspects of production could be discussed in terms of generic features instead of the specific choice of technology to be used. Still, this paper has been concerned with low-level analysis of manufacturing in the sense that it concerns choices of manufacturing technology and operational practice on the plant level as opposed to the supply chain perspective.

Product groups were implemented as parallel flows within the model. This technique allows high and low volume products, as well as other groups distinguished by some characteristic property such as slab width, to be easily introduced in the model. The effect of varying degrees of product differentiation can be assessed without including detailed data for individual products in the model.

In the case study, improvement goals were given by the firm's business strategy, and involved requirements for increased diversification with simultaneous cost reductions. A goal driven explorative procedure was used to reduce the data set such that only points representing the current state and target regions remained. This process is illustrated by Figure 12.

(Figure 12)

Figure 12a shows how a current state region, A, has been brushed, along with two desired future state regions (B,C). The frontiers indicate the limitations of cost versus range at each stage. The plant can operate anywhere above its current competitive frontier, but in order to open up a new frontier, innovations in manufacturing technology or routines are required (De Toni and Tonchia, 2005; Hayes and Pisano, 1996).

Figure 12b shows how the required change in design parameters can be identified. At the same time, the cost profile changes as seen in Figure 12c, with a reduction of tied capital in the first step, followed by a reduction of reheating costs in the second.

The combination of Monte Carlo simulation followed by goal-driven data analysis reveals the potential in flexible small lot steel refining and casting technology. This technology may not be available off the shelf, and the strategic implication must be the need to invest in the organisational skills needed to lead the development of new technology. Hence, change is not primarily about choosing what equipment to invest in; rather it is about developing the required organisational capabilities needed to identify how to best tailor manufacturing to handle the variation that follows from the chosen business strategy.

6. Conclusions

This paper presents an attempt to bring together system dynamics, cost modelling and explorative data analysis into a coherent framework that can aid the selection of improvement initiatives within the chosen manufacturing strategy.

The proposed five-step framework provides a structured method for evaluation improvement initiatives concerning new manufacturing technology and routines through dynamic cost modelling.

- A case study from the steel industry demonstrates the applicability of the five-step framework to support the choice of an improvement trajectory (Section 4).
- The use of visual explorative data analysis speeds up model development and improves model quality.
- Interactive linked plots facilitate a goal driven analysis. Regions of desired performance and product range are identified, and required changes in design parameters can be identified directly in corresponding linked views.

In summary, the use of dynamic cost models, within the presented five-step framework, provides a means to interpret the strategic goals, expressed e.g. as production capacity and cost, in terms of required capabilities. Strategic manufacturing initiatives can thereby be directed to support the chosen business strategy.

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Figure 1. The five-step dynamic cost modelling framework.

Figure 2. Steel production with continuous casting, reheating and hot rolling. The slab yard serves as buffer and inventory.

Figure 3. Order frequency for products entering the hot rolling mill in the case study: 7% of product variants represented 50% of the volume.

Figure 4. The three-layered cost model with processes, operations and cost components. The del contains four parallel product flows.

Figure 5. The interface between continuous casting and hot rolling, with order matching and scheduling.

Figure 6. Reheating modelled as a two step process.

Figure 7. Validation of simulated furnace power (solid) against plant data (-○-). Charging and discharging rates in the model were based on smoothed data from the production database.

Figure 8. Pruning of sensitivity results to remove configurations with high capital cost (+) and high reheating costs (×) from the main cluster (○). High-cost branches (a) are generally associated with reduced production capacity (b). Capacity imbalance may result in low furnace utilisation, or high buffering costs if the furnace is a bottleneck (c). Corresponding caster configurations fall in two distinct regions (d).

Figure 9. Brushing a desired two-step improvement trajectory towards increased product range and lower cost. Current configuration indicated by (×), first step by (●), and second step by (■).

Figure 10. Exploring simulation results for configurations that combine increased product range with low cost. Current configuration indicated by (×). Configurations satisfying first goal with increased charge weights indicated by (●), and with reduced charge weights (○). Second goal with increased charge weights (■), and with reduced charge weights (□).

Figure 11. Parallel coordinate plot showing design parameters and simulated performance in terms of total mean cost and production volume for current (A) and future (B, C) plant configurations according to Table 1.

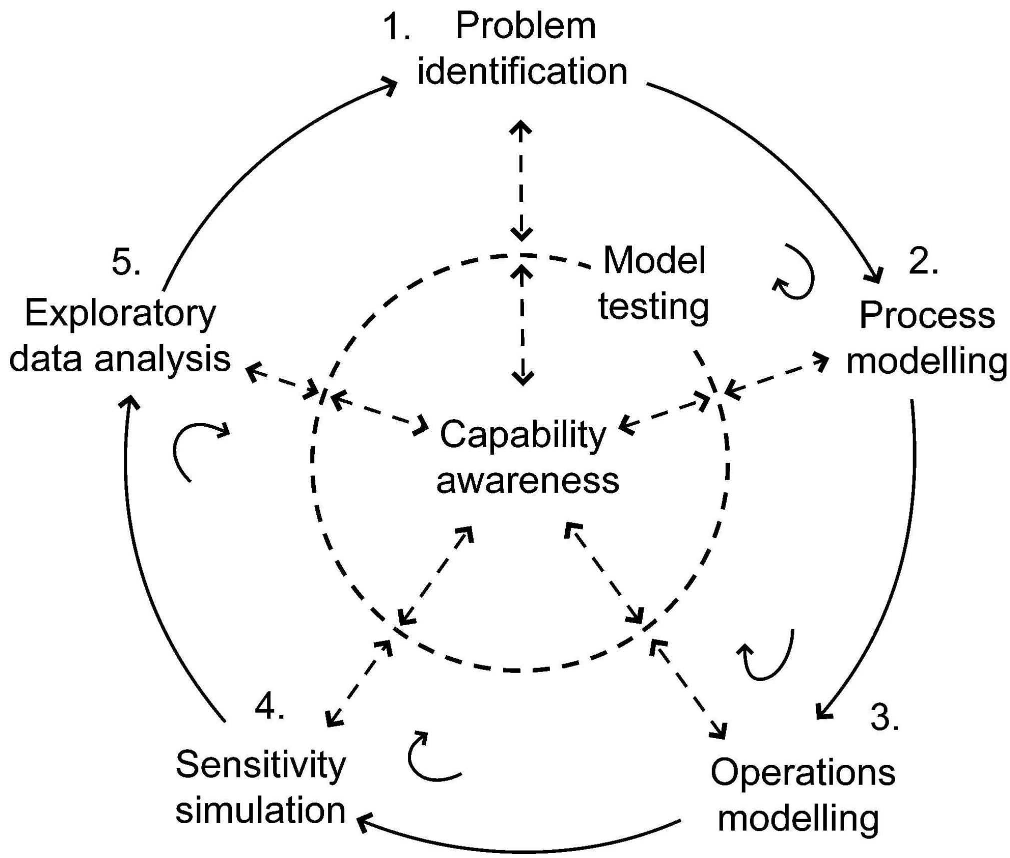
Figure 12. Goal driven explorative dynamic cost modelling: a) Current state (A) and improvement goals (B,C) are brushed. b) Process requirements are identified. c) Change in margin costs for tied capital, c_{WIP}, and reheating costs, c_E.

Table 1. Values of design variables for current configuration (A), and for future configurations (B, C) on suggested improvement trajectory.

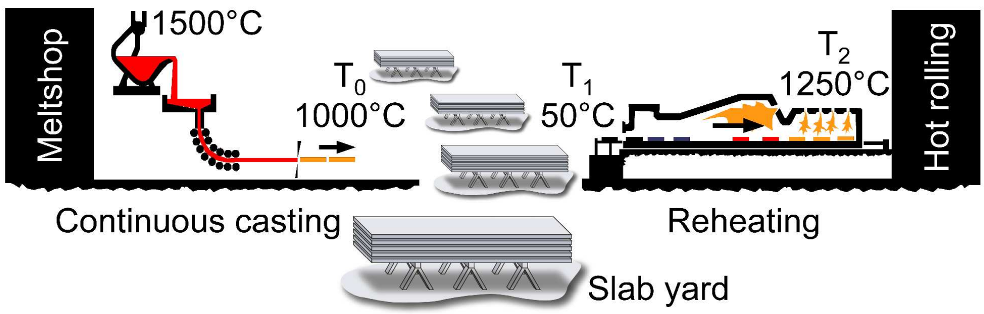
Configuration	A	B	C
Number of variants	150-200	200-300	300-400
CC setup time	1-1.5	0.6-0.9	0.33-0.5
Charge weight	90-100	70-90	50-70
HRM setup time	1-1.5	0.6-0.9	0.33-0.5
HRM schedule updates	0-1	2-3	4-6

Table 2. Manufacturing competence and capability requirements.

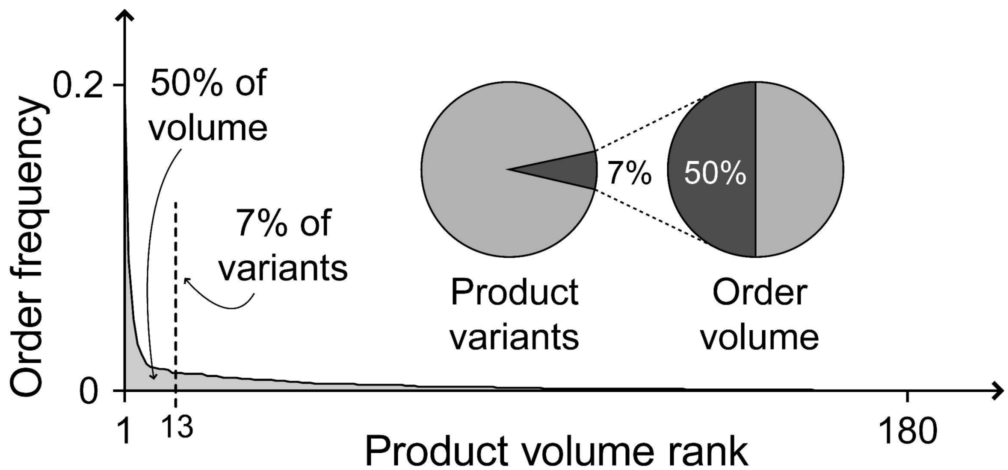
	Manufacturing competences	Capability requirements
a)	CC setup time reduction	Setup time reduction, development of flexible casting technology
b)	HRM setup time reduction	Setup time reduction, development of flexible rolling technology
c)	Feasible charge weights	Setup time reduction, development of flexible refinement and alloying technology
d)	Dynamic scheduling	Decentralised scheduling systems, review of scheduling policies



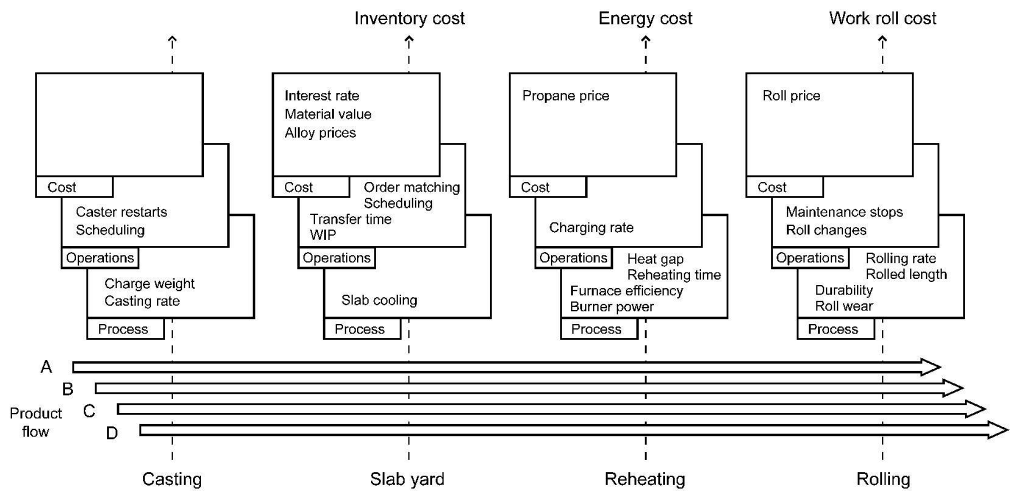
The five-step dynamic cost modelling framework.
166x141mm (600 x 600 DPI)



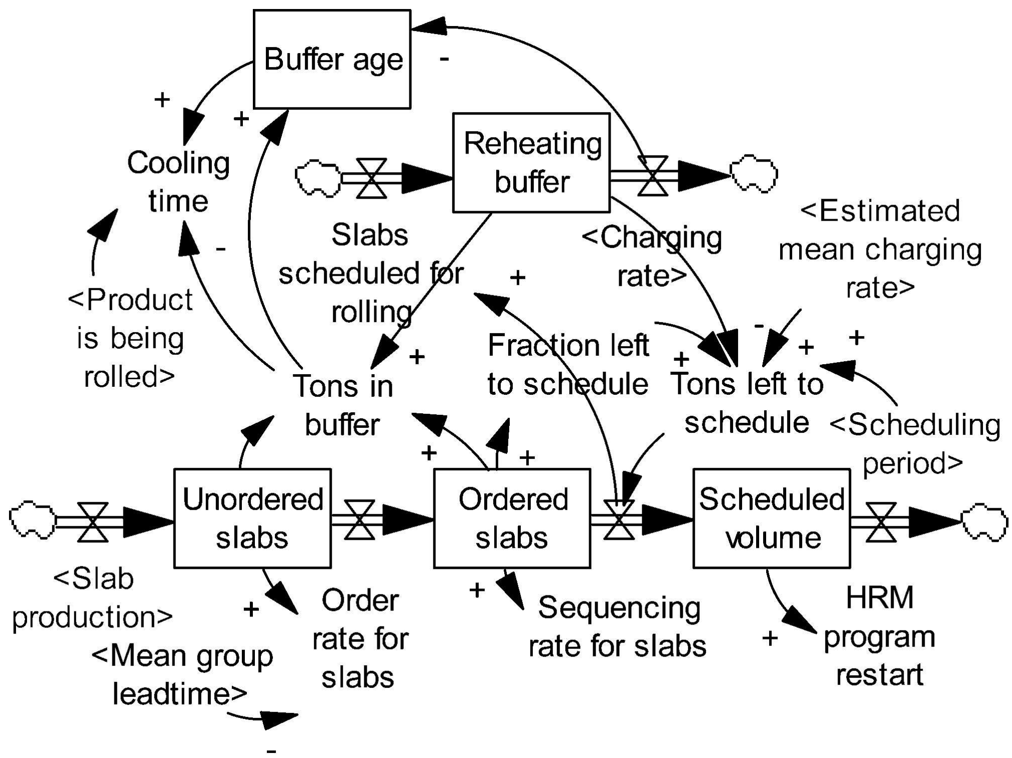
Steel production with continuous casting, reheating and hot rolling. The slab yard serves as buffer and inventory.
251x80mm (600 x 600 DPI)



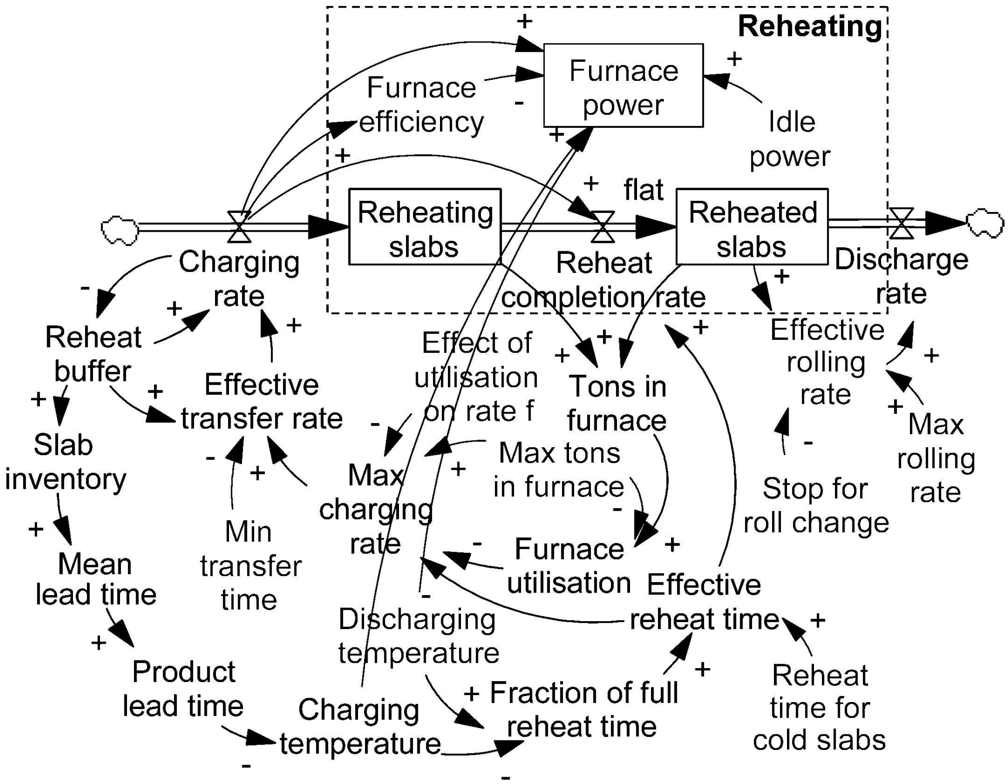
Order frequency for products entering the hot rolling mill in the case study: 7% of product variants represented 50% of the volume.
197x93mm (600 x 600 DPI)



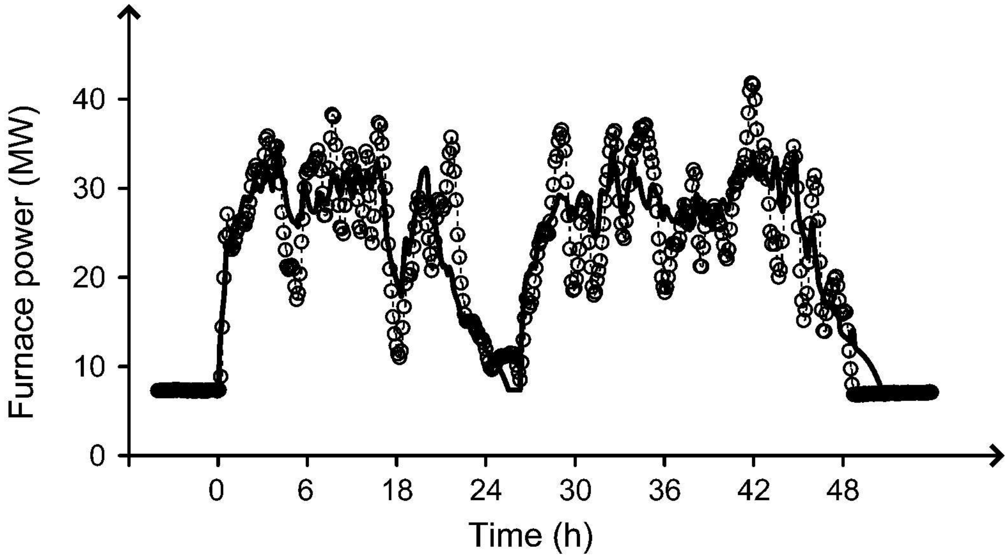
The three-layered cost model with processes, operations and cost components. The del contains four parallel product flows.
277x133mm (600 x 600 DPI)



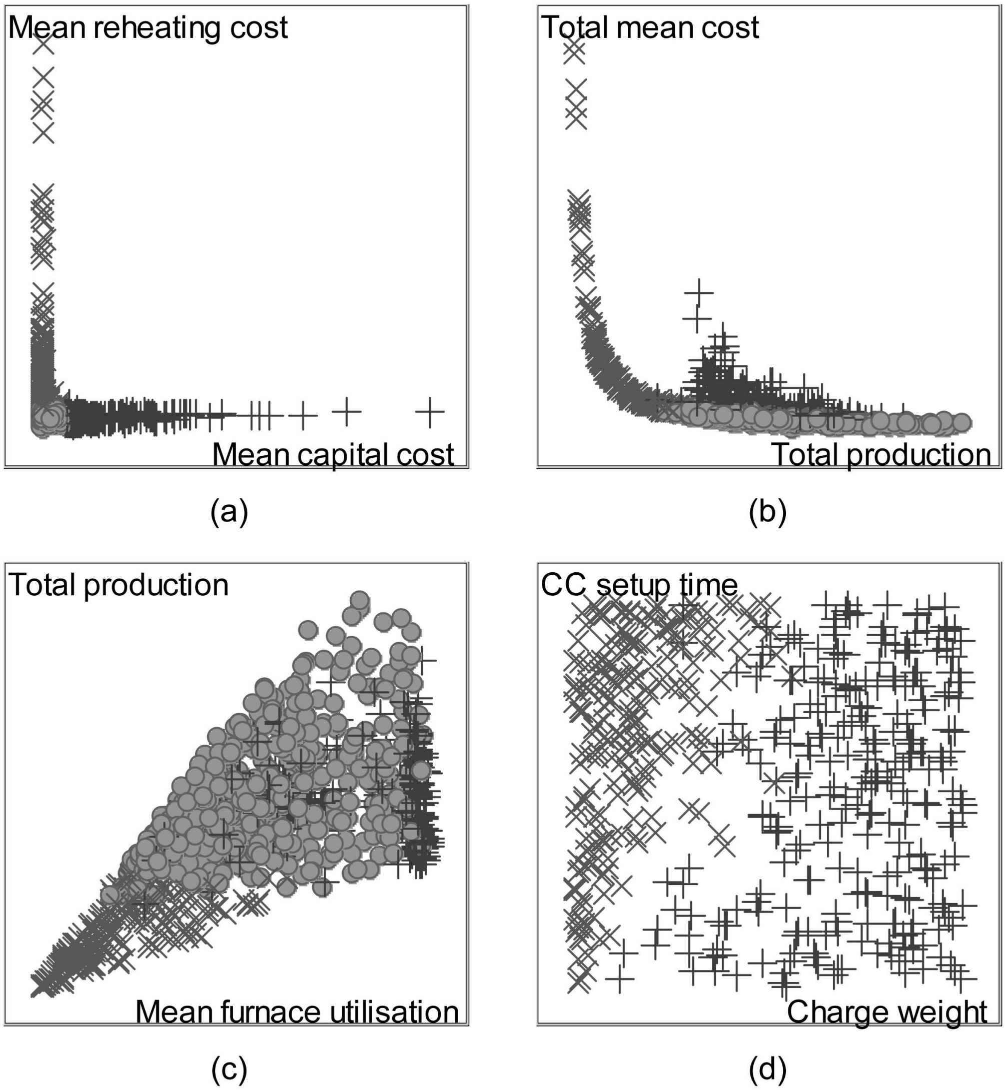
The interface between continuous casting and hot rolling, with order matching and scheduling.
84x64mm (600 x 600 DPI)



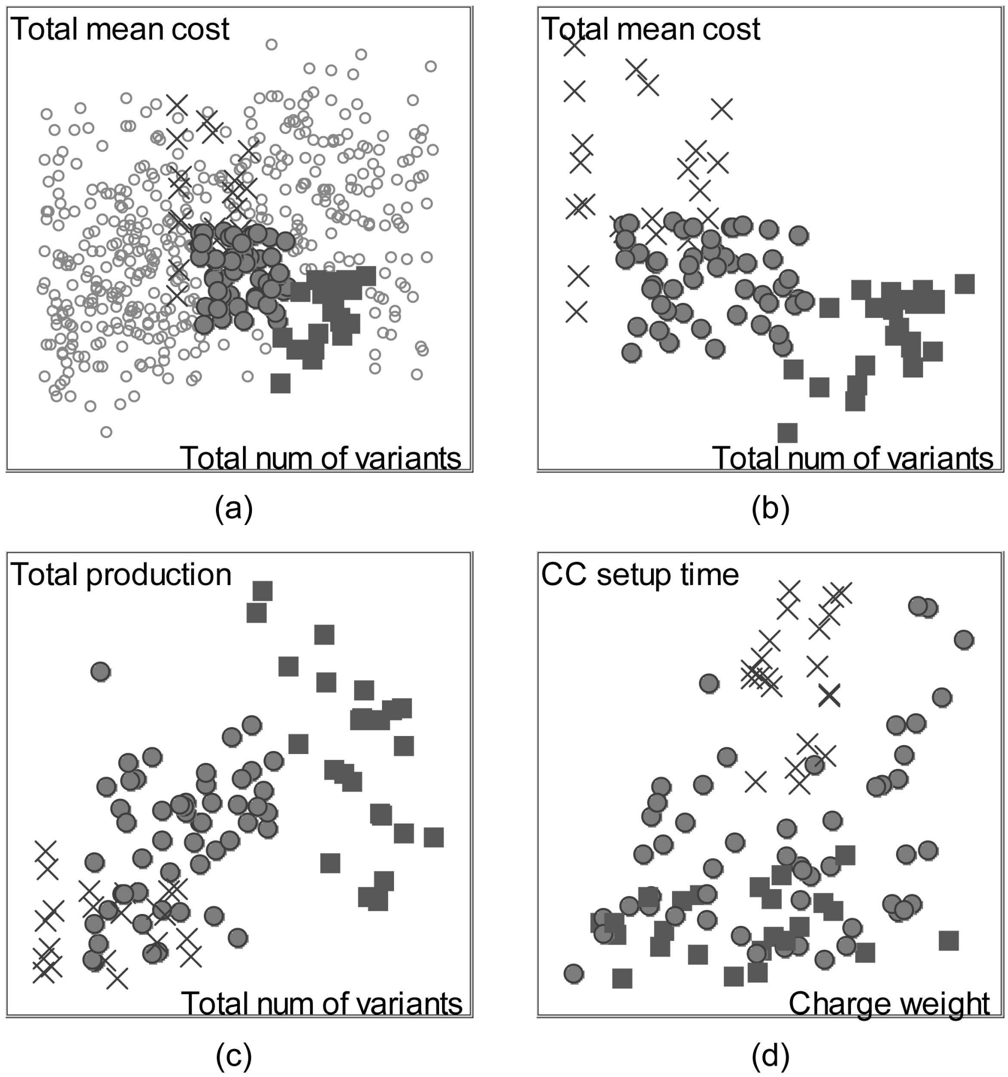
Reheating modelled as a two step process.
90x71mm (600 x 600 DPI)



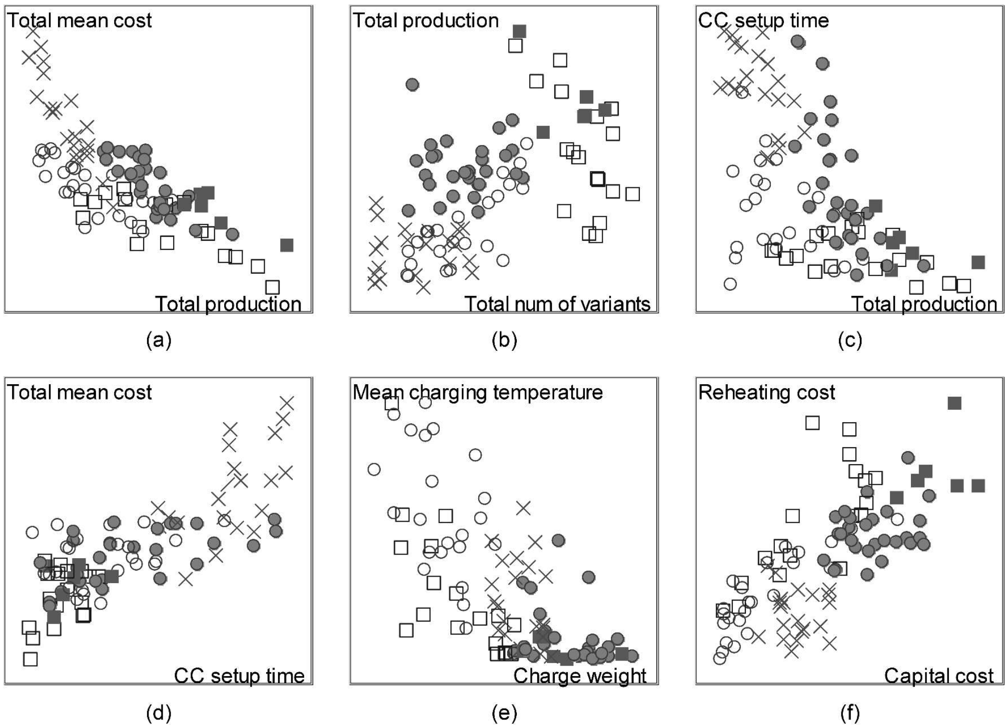
Validation of simulated furnace power (solid) against plant data (-○-). Charging and discharging rates in the model were based on smoothed data from the production database.
265x147mm (600 x 600 DPI)



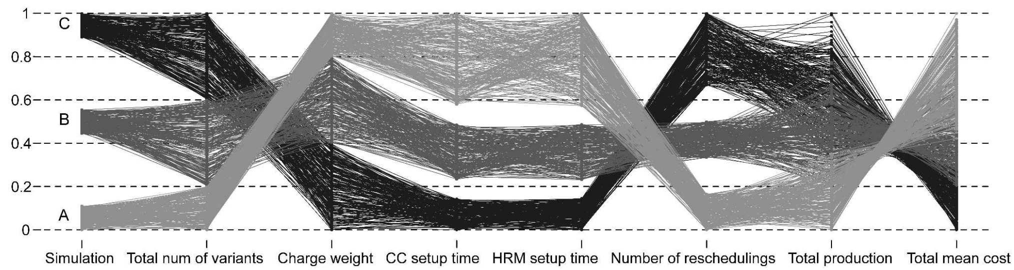
Pruning of sensitivity results to remove configurations with high capital cost (+) and high reheating costs (×) from the main cluster (○). High-cost branches (a) are generally associated with reduced production capacity (b). Capacity imbalance may result in low furnace utilisation, or high buffering costs if the furnace is a bottleneck (c). Corresponding caster configurations fall in two distinct regions (d).
99x107mm (600 x 600 DPI)



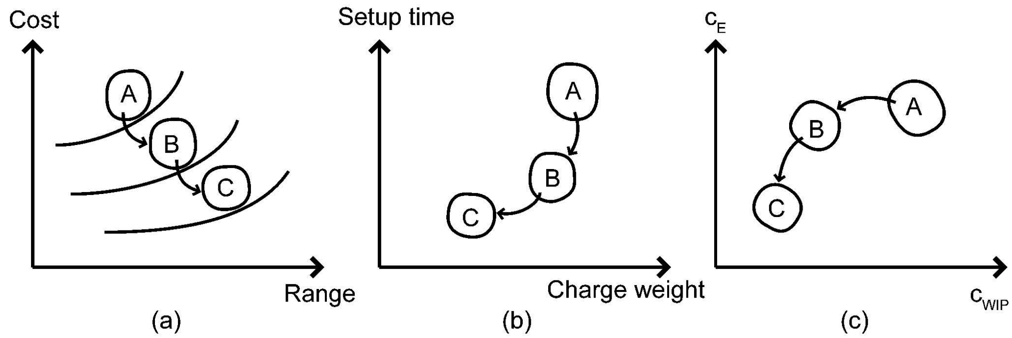
Brushing a desired two-step improvement trajectory towards increased product range and lower cost. Current configuration indicated by (×), first step by (●), and second step by (■).
98x105mm (600 x 600 DPI)



Exploring simulation results for configurations that combine increased product range with low cost. Current configuration indicated by (×). Configurations satisfying first goal with increased charge weights indicated by (●), and with reduced charge weights (○). Second goal with increased charge weights (■), and with reduced charge weights (□).
149x107mm (600 x 600 DPI)



Parallel coordinate plot showing design parameters and simulated performance in terms of total mean cost and production volume for current (A) and future (B, C) plant configurations according to Table 1.
262x68mm (600 x 600 DPI)



Goal driven explorative dynamic cost modelling: a) Current state (A) and improvement goals (B,C) are brushed. b) Process requirements are identified. c) Change in margin costs for tied capital, c_{WIP}, and reheating costs, c_E.
172x57mm (600 x 600 DPI)