Evaluation of machining strategies in cylinder-block manufacturing

Dynamic modeling

Maria Floriana Bianchi
Master’s Thesis
Abstract

In order to face and win the competitive manufacturing environment, which is particularly relevant in automotive industry, companies need to improve and update their machining lines and continuously evaluate their performance. This is usually done by analyzing the impact of the flow of material on the performances of the line. However, machining system parameters also have a great influence on the performance of a machining line. Therefore, it is extremely important to settle machining system conditions that take into account their effect on the system performance. This is particularly crucial in the case of the selection of new machine tools, new lines and, in general, when relevant decisions have to be taken. Nevertheless, there is no methodology or decision support system for the improvement of performance based on the analysis of machining system and related parameters.

This thesis aims to provide a framework for the evaluation of machining strategies in the context of a machine tool selection for a face milling process of a cylinder-block. The work will be based on a case study performed at Scania CV AB.
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## Abbreviations

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<td>SD</td>
<td>System Dynamics</td>
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<tr>
<td>DES</td>
<td>Discrete Event Simulation</td>
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<td>CLD</td>
<td>Causal Loop Diagram</td>
</tr>
<tr>
<td>S&amp;F</td>
<td>Stock and Flow</td>
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<tr>
<td>SPM</td>
<td>Special Purpose Machine</td>
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<tr>
<td>MC</td>
<td>Machining Center</td>
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<tr>
<td>OL</td>
<td>Old Line</td>
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<td>NL</td>
<td>New Line</td>
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1. Introduction

Manufacturing plays a crucial role for the economy of a nation and promoting research activities in the field of manufacturing is necessary to maintain and increase innovation and progress in a country. In particular, the automotive industry is of huge importance in this context. In Sweden, it employs half a million workers and the automotive supply chain is about 30 percent of the whole Swedish manufacturing sector. Moreover, the 12 percent of Swedish exportation comes from the automotive industry [1].

Within this sector, the manufacturing of engine components is vital and the selection of machining operations is critical in the production of these parts. Nowadays it is a primary issue to deliver well performing products [2] and, in order to fulfill this requirement for the produced vehicles, the quality of motor components is extremely important. Therefore, very tight tolerances in terms of geometrical accuracy and surface finishing have to be met. Moreover, because of the increasing geometrical complexity of these components and the continuous development of materials used for this purpose, more research efforts in process optimization are required.

On the other hand, manufacturing systems have to meet also other performance requirements, such as productivity, cost efficiency and robustness1. Performance indicators must be set and lines have to be continuously updated to fulfill new targets. Furthermore, the lean paradigm and, together with it, the concept of continuous improvement, are spreading

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1Robustness is “the ability of a system to resist change without adapting its initial stable configuration” [3].
over industries: therefore, performance targets are increasing and competition is now more than ever high. In order to achieve these goals, high improvements in machine tools and processes have been obtained. The advent of mass customization has also contributed to strengthen this challenging environment, since it asks for highly customized products at reasonable costs and therefore requires an increased number of product variants [4] [5]. This is enabled by flexible manufacturing systems with extensive use of automation and provides a higher level of technological complexity to be handled [4] [6].

1.1 Machining system

This background shows the main aspects that must be taken into account in a study within the field of machining. First of all, cutting processes have to be capable of producing high quality products. Moreover, machine tools have to be improved in order to fulfill productivity- and cost-related requirements. However, it is too simplistic to take into account these two aspects separately, since the machine tool and the process are continuously interacting with each other [7] [8]. The system comprising the two subsystems of machine tool elastic structure and cutting process is called machining system (Figure 1.1) [9].

![Figure 1.1 Machining system](image-url)
The manufacturing of components consists of several process steps performed in a sequence, where the raw material is progressively converted into finished parts. The final and intermediate part properties are results of all the previous individual process steps. As a consequence, a manufacturing system contains a chain of several units or machining systems.

In Figure 1.1, the machine tool elastic structure comprises the machine tool itself, the cutting tool, the work piece and the clamping system; while the cutting process is the actual machining operation that is performed.

The closed-loop shows that the cutting force applied to the machine tool structure will cause a relative displacement between cutting tool and work piece that will then modify cutting process parameters, in particular, chip thickness and depth of cut. Since the force is a function of these parameters, it will close this loop with a feedback to the machine tool elastic structure. Disturbances (D(t) in Figure 1), such as the tool wear and heating factors in the process will also affect the applied force and the relative displacement between tool and work piece.

Consequently, in machining, quality, cost and productivity performances do not depend only on the process and machine tool separately, but even on the effect of their interaction. Quality depends not only on the process or machine capability but on the overall machining system capability [7] [8]. It is then fundamental to choose machine tools that are well designed to machine pre-selected features and that can ensure the required accuracy together with the selected cutting process and manufacturing technology [10]. As for productivity performances and in order to reduce the production cost per part, processes and machines have to be jointly optimized to produce faster. However, this is not enough. Indeed, even though machine tools are optimized with high-speed processes to fulfill productivity and cost performance requirements, it may happen that they will produce defective products or they will wear out faster than they should [11]. This will then cancel the improvements in productivity and cost performances and will also create a waste of resources in terms of material, time spent to re-produce parts and money invested in machine tool maintenance.
Therefore, when the machining system has to be optimized, all the requirements of cost, productivity and quality need to be considered at the same time. Indeed, they are all linked to each other because of causal relationships. For example, a loss in machining system capability will bring higher need of inspections and therefore longer lead times to produce a part and higher costs for quality control. At the same time, if the machine tool works to be more productive – or actually only faster – than it should, more machine breakdowns will take place and the service life will be shortened. This will increase the downtime and which in turn will lead to higher maintenance costs, less productivity and hence higher production costs.

This means that, sometimes, decisions on the machining system addressed to improve the system from one perspective, can then cause problems in other aspects that will eventually give worse results than expected on the area that was supposed to be improved.

As a consequence, in the optimization of a machining system these points have to be taken into account: the performance requirements of quality, cost and productivity, the inter-relationships of machine tool and process that will affect the outcomes in terms of performance and all the effects that decisions on the machining system will have on machining system performance.

In this thesis, machining system performance indicators are the following:
- The machining system capability (quality), which is the capacity of the machining system to produce components that meet the design specifications.
- The productivity of the machining system, which includes two aspects: the number of products that the machine tool, with certain process conditions, is able to produce in a certain period of time and the implied machining system productivity\(^2\).

\(^2\)In this thesis, implied machining system productivity is defined as the productivity that considers the effects derived from decisions on the machining system that influence productivity, e.g. downtime or scrap rate.
• The cost of the machining system which includes all the costs directly or indirectly derived from all the decisions on the machining system.

1.2 Machining Strategies

In order to achieve good level of performance, it is necessary to make decisions on the machining system that are coherent to the requirements that have to be fulfilled.

The Oxford dictionary defines strategy as “A plan of action designed to achieve a long-term or overall aim” [12]. Therefore, a machining strategy is a plan, for the machining system, designed to achieve a long term overall aim, connected to machining system performance indicators.

In this thesis, machining strategies will be referred as the machining system conditions derived by all the decisions taken with the objective of optimizing the machining system in respect to pre-selected performance criteria and related targets.

Decisions related to machining strategies can regard both the modules of the machining system, which are the machine tool elastic structure and cutting process, and other external factors that interact with it. Examples of these choices can be: the selection of a machine tool; that of a cutting tool or clamping system to use; the values of cutting process parameters and even the work piece material; the decision of which takt time to choose; the choice of how much preventive maintenance to have and how to distribute it over time and so on. In literature, there is a lack of a unified concept for the evaluation of machining strategies and nowadays companies have to develop very complex models every time they have to take these kinds of decisions.
1.3 Objectives and research questions

The objective of this work is to develop a framework to analyze machining strategies. In particular, this study will provide a decision support model for the evaluation of machining strategies in the context of a machine tool selection for face milling operations used in the production of cylinder-blocks.

This work is a part of a bigger project in which a unified framework and model will be built with the scope of evaluating machining strategies to test different line concept scenarios, therefore even considering other cutting processes.

Since it is really important, in order to get reliable simulation results, to have data from real machining systems [7], the model is supported by a case study performed at Scania CV AB.

The approach will take into account machine tool and process parameters and machining performance indicators.

Research questions will be:

1. *Is it possible to build a model for the evaluation of machining strategies that takes into account how the machining system and its performances are related to each other? And, if so, is SD a suitable methodology to do it?*

2. *Which are the main drivers to improve machining system performance?*

3. *How and how much will the drivers affect machining system performance?*

4. *Which machine tool concept is the most suitable for the face milling of the two cylinder-block sides?*
Knowing how different parameters are related to each other and how drivers influence machining system performance is useful to understand how the system will behave when some source of variation arises, such as a development of work piece material or new dimensional requirements due to design and technological innovation.

Moreover, a model describing the relationship between all the inter-related variables and the consequent dynamics of the system would help in the understanding of the causes of errors, that is, if they come from the process, from the machine or even which machine component has caused a deviation.

1.4 Delimitations

Since this study is part of a project that has a rather wide scope, it is worth to point out the delimitations of this thesis work in order to better define it and give clearer recommendations for future work on this topic. The main delimitations and considered aspects in this work are shown in Figure 1.2.

First of all, the order rate is taken into account: based on the demand, the desired throughput is considered. The machining system is, indeed, set up in order to produce the desired amount of components and to fulfill quality requirements that, in turn, depend on the machining system.

The machining system, together with the achieved quality will provide a certain productivity performance. Depending on productivity and quality results, the chosen setup will have a final cost. In this case, cost is mainly considered as an output. Productivity and cost, in the model, depend on parameters that will be explained in the following chapters. Eventually based on the reached (and reachable) level of productivity, the desired throughput is determined.
The main limitations of this case study are the following:

- First of all, this study is limited to the analysis of machining strategy in the selection of a machine tool, for specific features and considering only one material. Therefore, the robustness of the solution when the work piece material or specifications are changed is not considered. This also means that in the evaluation of productivity performance, the effects of waiting time due to other machines in the line and starvation are not considered.

- Moreover, the machining system capability, in this work, will be considered as a constraint and not as a parameter to monitor (that is why in Figure 1.2 it is marked in red). This decision comes from the fact that quality depends on several factors and – in order to test
the potential of the model – it has been considered more appropriate to consider it as a constraint rather that give a too rough approximation of it. In order to add quality aspects, tests to verify the validity of the data would have been necessary.

- As for the machining system, the machine tool elastic structure subsystem main variable – the static stiffness – has not been taken into account since data of it were not available. However, with the help of academic, production and maintenance professionals, the machine tool has been considered in order to give limits to the cutting parameters and ensure that they will not badly affect quality and to consider the maintenance. The kind of clamping system is not taken into account as well. With regard to disturbance factors, heating phenomena during cutting and consequent variations of parameters are not taken into account.

To sum up, main machining system parameters and machining system performance indicators using in this case study are the following.

Machine and process parameters are:
- Cutting tool (number of inserts and diameter) for each operation
- Cutting parameters: feed rate, feed per tooth, RPM and cutting speed
- Tool life and tool wear

Performance-related parameters are:
- Cycle time
- Throughput
- Uptime
- Cost per part
- Efficiency

Also these parameters will be defined in the following chapters.
1.5 Thesis outline

The next chapters of this thesis are structured as follows: Chapter 2 will provide a description of the methodology and tools used in this study. In chapter 3 a comprehensive description of the problem object and of the case study will be given. In chapter 4 a model for the evaluation of machining strategy applied to the case study will be shown. In chapter 5 a discussion on the results and outcomes of the model will be presented. Finally, chapter 6 will conclude this work with a final summary and by giving recommendations for future work.
2. Methodology

The framework described in the introduction shows the huge complexity of the actual manufacturing environment. ElMaraghy [6] states “The challenges facing industry now are characterized by design complexity that must be matched with a flexible and complex manufacturing system as well as advanced agile business processes”. It the literature it is common to consider the manufacturing system as a complex system [6] [13] [14].

A complex system can be defined as a system that “usually consists of a large number of members, elements or agents, which interact with one another and with the environment” [6]. The machining system, which is a part of the whole manufacturing system, is constituted by several elements (which in turn compose its subsystems), related to each other and also interacting with the external environment. Therefore, this can be considered as a complex system.

As a consequence, while evaluating machining strategies, a holistic approach is essential to take into account all the different performance criteria and the complexity closely related to machining system. Sterman [15] underlines the importance of having such an approach in analyzing complex systems and states: “If people had a holistic worldview, it is argued, they would then act in consonance with the long-term best interests of the system as a whole, identify the high leverage points in systems, and avoid policy resistance”.

Heeding the objective and the research questions of this work and recognizing the complex nature of the machining system and of the
decisions regarding machining strategies, System Dynamics (SD) is the chosen modeling methodology used in this study.

2.1 System thinking and System Dynamics

System thinking is an approach, basis of System Dynamics (SD), founded by Jay Forrester in 1956 [16].

In order to fully understand what system thinking is and the benefits that it can bring to the study of a problem, it is worth to compare it with the traditional analytic approach.

The world “analysis” derives from the ancient Greek and its root means “to separate something into its constituent elements”: this means that the traditional analytical approach is based on breaking up a problem into small pieces that are then separately studied. On the other hand, the system thinking approach studies a problem with a focus on the interaction in between the different elements within a system [17].

Inversely, a system thinking approach permits to understand complex dynamic systems and to detect the feedbacks that characterize them. The highest the complexity of a system is, the more effective the system thinking approach will be to study that system, and the more the results obtained with the two methods will get very different from each other.

While system thinking is an approach to study a problem, System Dynamics (SD) is a methodology which uses the system thinking approach to model and simulate the behavior of complex, dynamic systems with the aid of computer programming [18]. Sterman defines it as “a method to enhance learning in complex systems” [15].

SD has been applied to a wide variety of problems and subjects. However, regardless the fields of application, the systems addressed in SD have some common points:
- These systems are dynamic, complex systems which usually have an underlying causal structure characterized by non-linear relationships between variables and internal accumulation processes that cause time delays and create feedback loops. This implies that, in these systems, when a decision is made, its effect might be delayed on time, thus making it harder to understand the causes of unexpected system behavior.

- Moreover, these systems are usually composed by variables that are transversal to different topics and involve different stakeholders: this will increase the challenge of studying the system and its related problems.

Considering this, SD modeling and simulation is particularly useful for the evaluation of decisions and policies in the field of complex dynamic systems, since it allows to see which will be the effects of these decisions on the system.

### 2.1.1 Steps of System Dynamics modeling

SD methodology has its basis lying on the principle that the behavior of a system is caused by its own structure [15]. Therefore, the core of SD is to understand the structure of the system that has to be analyzed and to model it properly. Figure 2.1 shows the main steps of SD modeling.

![Figure 2.1: Steps in SD modeling](image)
First of all, a thorough study of the system has to be carried out in order to understand its structure.

Then, a dynamic hypothesis has to be developed: this is a fundamental step in order to make a valid SD model. Indeed, the expression of the system structure through a diagram showing the feedbacks and causal interdependencies between the fundamental variables or sub-systems helps to identify the behavior of the system.

The next stage is the actual modeling and simulation of the system. The model should, of course, mirror the structure previously derived and the simulation results should then confirm the forecasted behavior.

Finally, policies have to be designed and modeled to see their effects on the system and take decisions subsequently. Of course, the whole process could be re-iterated in order to verify the validity of new policies.

2.2 System Dynamics Tools

In order to apply SD methodology, as it was previously stated, it is necessary to model the system structure, to verify the dynamic hypothesis and eventually perform the policy analysis. Two main modeling tools are used to perform these steps: the causal loop diagram and the stock and flow diagram.

2.2.1 Causal Loop Diagram

The causal loop diagram shows the causal relationships between the main variables of a system and underlines the feedbacks that determine its behavior.

Feedbacks can be of two types: positive (or reinforcing) loops and negative (or balancing) loops. Positive loops amplify any change in the system, while negative loops counter-balance changes in the system.
The arrows are associated to a sign (+/-), which is called “polarity” and shows the positive or negative causal relationship between the variable from which the arrow is departing (the cause) and the variable to which the arrow is directed (the effect). Zero or an even number of negative signs in a feedback loop within a CLD will provide a positive loop (+ R), while an odd number of negative signs indicates that the feedback in the system is negative (- B).

![Figure 2.2: Examples of CLD](image)

From a mathematical point of view, a positive polarity – as it is in Figure 2.2 a) – means the following:

\[\frac{\delta C}{\delta B} > 0\]

On the other hand, a negative polarity – as shown in Figure 2.2 b) – is associated to the relationship:

\[\frac{\delta C'}{\delta B'} < 0\]

### 2.2.2 Stock and Flow diagram

While the causal loop diagram serves as a conceptual representation of the system in order to understand the nature of the main feedback loops, the stock and flow diagram is a way of modeling dynamic systems through building blocks to show the phenomena of accumulation of entities and the interactions between the different
variables. This diagram is used to simulate the behavior of the system and includes all the numerical relationships between the system variables.

The main building blocks of a stock and flow diagram are shown in Table 2.1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
<th>Symbol</th>
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<tr>
<td>Stock</td>
<td>Accumulation of a flow, it describes the state of the system</td>
<td>![Stock]</td>
</tr>
<tr>
<td>Flow</td>
<td>A rate that makes a stock increase (positive inflow) or decrease (positive outflow)</td>
<td>![Flow]</td>
</tr>
<tr>
<td>Converter</td>
<td>A variable that contains an equation or a constant</td>
<td>![Converter]</td>
</tr>
<tr>
<td>Connector</td>
<td>A causal relationship between two variables</td>
<td>![Connector]</td>
</tr>
<tr>
<td>Cloud</td>
<td>The boundary of the system</td>
<td>![Cloud]</td>
</tr>
</tbody>
</table>

Table 2.1: Building blocks of S&F diagram in Stella/iThink

The accumulation of stocks through flows that causes delay is one of the main phenomena detected by SD modeling and simulation. The stock is a quantity that accumulates a flow. A stock represents the state of the system at each time \( t \); the flow, instead, represents the rate at which the state of the system changes in a period \( t+dt \).
As it is stated in Table 2.1, flows are of two types: inflows and outflows. Inflows – if positive – cause an increment of the stock, while outflows – if positive – determine a reduction of the stock. Considering a level and the rates influencing it, the stock, over an integration period will be increased or decreased by the net rate of the flows. Therefore, the state of the system depends only on the initial level of the stock and on the difference between the flows influencing the stock (net rate). If the net rate is positive, the stock will increase and vice versa. Stocks can be only influenced by flows.

It has already been mentioned that stock and flow relationships cause delays. Indeed, the concept of delay is incorporated in the definition of a stock as:

\[
Stock(t) = Stock(t_0) + \int_{t_0}^{t} Flow(t)dt
\]

Where
t_0 is the initial time
Flow(t) = Inflow(t) – Outflow(t) is the net flow
dt express the interval between calculations and is expressed in the unit chosen for the model.

Figure 2.3 shows a simple example of stock and flow diagram with a positive and a negative feedback loop. The polarities are here shown to make the system more understandable.
A stock will be filled at a certain rate (the inflow), which depends on the actual level of the stock and on the time needed to fill the stock. This structure describes a reinforcing loop, since – if the time is constant – if the stock increases, the inflow will be higher, thus making the stock increase as well. However, at the same time, the stock is emptied with a rate (the outflow) that depends on the level of the stock and on the needed time to empty it. This structure, instead, describes a balancing loop: if the time to empty the stock is constant, while the stock increases, the outflow will increase as well, but this will in turn reduce the stock level, thus limiting the outflow. It is important to notice that, if there is no single line arrow (like the red ones in the figure) going from the stock to a flow, the flow will not depend by the stock. From this example, it can be noticed how the CLD and the S&F diagram can be jointly used to understand the dynamics of the system and simulate it.

The example just explained shows that the accumulation effect from flows to stocks is not instantaneous but takes places over a certain period of time. The delayed effect of the flows on the stocks causes the main dynamics of the system.

Delays can be of two types: material and information delays. In material delays, the delay is caused by a material accumulation in a stock at a certain rate. On the other hand, information delays occur
when information has to be handled and this requires time. Information delays are based on the fact that, sometimes, the perceived value of an entity is delayed from the actual value of that variable. Information delays are modeled in stock and flow diagrams in the following way:

![Diagram](image)

**Figure 2.4: Information delay structure [19]**

This structure is analogue to a weighted average and can be then used to filter out high frequency noise as a smoothing through a moving average [15].

In simulating systems with stock and flow diagrams, the choice of \( dt \) is very relevant. It expresses the resolution of the model: if the unit for the model is month and \( dt \) is 0.25, this means that all the state variables will be calculated every fourth of a month. The lower the \( dt \) is, the more precise will be the simulation. However, a compromise between accuracy and speed of simulation has to be achieved [19]. One thing to keep in mind is that the \( dt \) must not be higher than the shortest time delay: if this happens, the dynamics caused by the delay will not be detected by the simulation.
### 2.3 Modeling manufacturing processes

Simulation is one of the most used methods for decision making processes. Of course, the choice of the simulation technique is of huge importance to have reliable results. The two main simulation approaches for manufacturing systems are continuous simulation and discrete event simulation (DES). The former is suitable for systems with continuously changing variables [20]; the latter, instead is more indicated for systems in which variables are changing in discrete steps [21].

SD is a methodology that uses continuous simulation and it is suitable for systems in which feedbacks affect significantly the system behavior by causing dynamic changes [22].

The table below shows the main differences between SD and DES with respect to different aspects.

<table>
<thead>
<tr>
<th>Compared aspect</th>
<th>SD</th>
<th>DES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature of problems modeled</td>
<td>Strategic</td>
<td>Tactical/operational</td>
</tr>
<tr>
<td>Feedback effects</td>
<td>Models causal relationships and feedback effects</td>
<td>Models open loop structures; less interested in feedback</td>
</tr>
<tr>
<td>System representation</td>
<td>Holistic view</td>
<td>Analytic view</td>
</tr>
<tr>
<td>Complexity</td>
<td>Wider focus, general and abstract systems</td>
<td>Narrow focus with great complexity and detail</td>
</tr>
<tr>
<td>Data inputs</td>
<td>Qualitative and qualitative, use of anecdotal data</td>
<td>Quantitative, based on concrete processes</td>
</tr>
<tr>
<td>Model results</td>
<td>Provides a full picture (qualitative and quantitative) of system performance</td>
<td>Provides statistically valid estimates of system performance</td>
</tr>
</tbody>
</table>

Table 2.2: Comparison between SD and DES[23]
In this work, SD has been chosen as suitable simulation approach for many reasons.

First of all, although the study of the problem will be at the operational level, reaching this degree of detail, does not exclude to have a holistic approach. Indeed, the focus will be on strategic goals that involve different stakeholders and are transversal to different topics: machining system parameters, operations management, maintenance and asset management.

Secondly, it is of interest to understand the interrelationships between variables and how the feedbacks in the system will influence its behavior. Actually, in this case, some of the feedbacks are kind of control loops: this is connected to the origins of SD, which is based on the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering [15].

Moreover, in this case, the interest is more focused on modeling and understanding the dynamics of the system than the mathematical relationships between variables. Indeed, some variables are connected through qualitative relations. With discrete event simulation, it would be very hard to link together variables coming from different systems in a qualitative way.

As for the results, as it has been specified in the research questions, the focus will mainly be on the behavior of the system variables and performance, than on synthetic, statistically calculated values.

Currently, SD has never been applied to this topic and with such level of detail inside the process: modeling the machining system parameters at a higher system level, linking them to performance indicators and operational variables. This innovation is another motivation of this research project.
3. Problem Description

The previous chapters show the importance of considering the whole machining system and its performance indicators in order to take decisions that have a good long-term effect to achieve high machining system performances and of having a framework to evaluate machining strategies.

This is especially relevant when new setups in machining lines have to be settled or new machine tools have to be selected. In this study, a model for machining strategy evaluation will be developed for the selection of a machine tool for face milling, to be used in the production of cylinder-blocks. As it was mentioned in the introduction, this work will be based on a case study at Scania CV AB.

The objective will be to evaluate two kinds of machine tool concepts: special purpose machine and machining center. This analysis will consider the outcomes from the choice of the two machine tool concepts in terms of cost, and productivity performance. In this case, quality will also be considered but, being an essential requirement, having conforming products will be set as a constraint to the model parameters. This will, of course put limits to the values that will in turn affect the other performance indicators and that depend on the chosen machine tool and machining strategy. This will be further explained in chapter 4.

As it was mentioned in the introduction, this study is part of a project aiming at evaluating machining strategies in the wider context of a line selection: the main scope is to consider the differences between the two concepts of transfer line with special purpose machines and a cellular
layout with machining centers for the machining of cylinder block. In particular, the proposed idea would be a cellular layout concept with a combination of the two technologies of special purpose machines and machining centers.

In this chapter a description of the problem will be provided. However, before describing the current situation analyzed in this case study at Scania CV AB, it is worth to explain the main differences between the two kinds of machine tools that will be object of the study problem.

3.1 Classification of manufacturing systems

Basing on the needs of production volume and product variety that a manufacturing system has to produce, there can be three basic types of manufacturing systems:

- Transfer lines, having fixed automation, in which all the processing steps are fixed and depend on the equipment configuration.
- Flexible manufacturing systems (FMS), having the capacity of producing medium production volume and a medium level of product variety; they are arrangements of machining cells, numerically controlled.
- Stand-alone NC machines, that provide a high level of flexibility, thus allowing to produce

![Figure 3.1: Example of a transfer line](image)

The first two kinds of manufacturing systems will be taken into account in this work. However, taking into account that a component is produced through a series of processes performed in one or more machine tools and
that – as it was previously stated in the introduction – they can be seen as a chain of machining system, in this work, the focus will be only on a manufacturing unit, thus on a single machining system. Therefore, from now on, the work will be carried out at the machine tool level.

Transfer lines and FMSs are equipped with different kinds of automation: in particular, transfer lines with special purpose machines (SPMs) and FMSs with machining centers (or multi-purpose machine). As their names suggest, the main difference between them is the range of use of the two concepts.

A special purpose machine is designed for one scope: this means that it usually has non-changeable tools in a fixed position and probably more than one spindle, in order to make different machining operations at the same time. For example, in the case of drilling different holes, a special purpose machine could have one spindle with several drills connected to a “drilling box”, machining the holes all in once. Usually special purpose machines are very stiff, since they move along and around only the axes needed to make a certain operation or set of operations.

A machining center or multi-purpose machine is a kind of machine tool that is designed to sustain changes. This means that it usually has three to six axes and only one spindle, where different tools can be mounted on. It has more degrees of freedom and is much less stiff than a special purpose machine since its components move along different directions.

Of course, both machining centers and SPMs have pros and cons and should be used in different conditions.

Machining centers have the main advantage of great adaptability to change: if a change in a product design arises or a new variant is added, they can be easily programmed to machine different features. Machining centers usually cost less than SPMs and have a simpler structure in terms of components. However, they are much less stiff than SPMs: they therefore wear out faster and have more problems related to vibrations, needing more
corrective maintenance than SPMs. They must be used if the features to be machined or the product design are subjected to change.

As for special purpose machines, they are stiff and they can therefore stand quite tough cutting conditions, thus giving higher productivity than machining centers. This is also reinforced by the fact that they can stand higher forces that arise with bigger cutting tools: therefore – for example, in the case of a face milling – they do not need to pass several times in order to machine a wide surface and they hence require less time to machine a part. Moreover, they usually need less corrective maintenance than machining centers since they are more robust and they have longer service lives. Nevertheless, SPMs usually require higher costs of investment than other machine tools and despite they have longer service lives, they also have a higher number of components that risk to wear out or be substituted. Moreover, they have the main disadvantage of being quite inflexible: indeed, if there is the need to change the process plan or the component design, very high costs and long time will be needed to modify the structure of this kind of machine tool to adapt to changes. For these reasons, SPMs should be used to machine features that do not change from one product to another and that remain the same in the same product through time. However, in this case, it has to be evaluated the financial convenience to use one machine concept or the other. Indeed, since SPMs are usually faster, it could be necessary to buy more than one machining center to achieve the same productivity of a SPM: this could imply higher or lower costs, depending on machine, operational and maintenance conditions, therefore on the chosen machining strategies.

### 3.2 The current setups

Scania CV AB manufactures different variants of cylinder-blocks. The variant object of this case study is DC13, which is a straight cylinder-block with six cylinders. They are produced in grey iron and they are manufactured through two main production steps: casting and subsequently machining.
In the same lines, Scania also produces another cylinder block variant, which differs from DC13 only for the fact that it is manufactured in CGI\(^3\). The latter is another kind of cast iron, newer than grey iron, which has higher resistance to metal fatigue and can better fulfill the combination of strength and lightweight [24], but having a lower machinability than grey iron, therefore it needs lower values for cutting parameters (especially lower cutting feed and speeds) to be machined.

The production of cylinder-blocks in CGI is gradually substituting that of components in grey iron. However, since both the examined lines, and therefore the machines, have optimized cutting parameters for grey iron but not for CGI, in order to use real data from the company, this study takes into account values of cutting parameters used to machine the DC13 variant (in grey iron).

3.2.1 The lines

DC13 cylinder-block is machined in two machining lines. One is a transfer line, with mainly special purpose machines (SPM); the other is a line principally composed by machining centers, which are multi-purpose machines. In this thesis the two lines will be respectively called “Transfer line” and “FMS”. For Scania nomenclature, the two lines are, instead called “old line” and “new line”.

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\(^3\)Compacted Graphite Iron
3.2.2 The machining process

The machining process that will be the object of this study is the face milling of the two long, lateral sides of the cylinder-block, which are the primary datum of the part within the whole process plan. As it can be seen in Figure 3.2 and 3.3, the two faces are composed of two features each one, an upper and a bottom feature. Both the faces are milled in two steps: roughing and finishing.

![Figure 3.3: Features 3300(1) (in the red box, with red contour) and 3300(2) (in the green box, with red contour)](CONFIDENTIAL)

3.2.3 The machines

As it was mentioned before, two machine concepts will be compared: special purpose machine (SPM) and machining center. The current lines where the DC13 cylinder block is machined have a SPM and a machining center in the old and new line respectively.

![Figure 3.4: Features 500(1) (in the red box, with red contour) and 500(2) (in the green box, with red contour)](CONFIDENTIAL)
The special purpose machine has two main stations: a milling station and a drilling one.

The machine has a moving table where the part is positioned. When the part enters the machine, it passes between the four tools that do the rough milling operation. After that, the spindles move along the z-axis and let the work piece go back to the initial position and then be machined in the same
way, but for the finishing operation. Finally, the holes are drilled and the part can be unclamped and moved to the second machine.

![Image of left-side and right-side tools and table in SPM](image)

Figure 3.7: Left-side tools (left) and right-side tools and table (right) in SPM

The milling station is the one that is mainly considered in the model and consists of four spindles, two on the left side and two on the right side. Each of them is connected to a large milling cutter, each of them performing both rough and finish face milling of one of the four features of the product. The drilling station consists of a spindle with a big tool-holder with multiple drills. The dimensions of the milling cutters in the SPM and machining center are shown in Table 3.1 (SPM) and 3.2 (machining center). In the appendix a bigger table can be found, displaying the main cutting data and cycle times for the two machines.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool diameter R</td>
<td>250 315 355 250</td>
<td>mm</td>
</tr>
<tr>
<td>Tool diameter F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of inserts R</td>
<td>36 50 48 32</td>
<td></td>
</tr>
<tr>
<td>Number of inserts F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of edges/insert R</td>
<td>12; 4 8; 4 12; 4 8; 4</td>
<td>Normal; Viper</td>
</tr>
<tr>
<td>Number of edges/insert F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Tool data for SPM
The machining center, instead, is a horizontal, 4-axes multi-purpose machine. It has only one spindle, on which different tools can be mounted.

Considering the process plan for the machining of DC13 cylinder-block, the machining center performs the same cutting operations, apart from some more holes that the SPM drills and that are machined later in the new line. However, the machining center has only one horizontal spindle. The tools are changed between one cutting operation and another. Therefore, first of all the part is clamped and a tool (smaller than those in the SPM) makes the rough milling operation in the four features. After that, the tool is changed and the finishing is done by a second milling cutter, also this one, smaller than the mills in the SPM.

The tools in the machining center are too small to perform the cuts in only one pass, as the tools in the old line do and they also mill the four features separately: therefore it will need more time to perform the cutting operations.

### 3.2.4 Machine tool components and maintenance

The main differences of the two machine tool concepts are not actually the only taken into account in this case study. Indeed, independently from the machine tool concept, a machine tool can have different components that will imply different performance and costs. It is then worth to discuss the number and type of machine tool components that will be considered in the model. The number and type of each component are displayed in Table 3.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool diameter R</td>
<td>500(1) 160</td>
<td>mm</td>
</tr>
<tr>
<td>Tool diameter F</td>
<td>500(2) 200</td>
<td></td>
</tr>
<tr>
<td>Number of inserts R</td>
<td>3300(1) 22</td>
<td></td>
</tr>
<tr>
<td>Number of inserts F</td>
<td>3300(2) 10</td>
<td></td>
</tr>
<tr>
<td>Number of edges/insert R</td>
<td>500(1) 12</td>
<td></td>
</tr>
<tr>
<td>Number of edges/insert F</td>
<td>500(2) 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3300(1) Variable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3300(2) Values</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 mm</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.2: Tool data for MC**
The only three components that are taken into account in this case study are the ball screws, the guideways and the spindle bearings. They are three of the main machine tool components in terms of machine capability. Ball screws and spindle are movable components, while the guideways are the tracks on which the table and the columns are moving: they are therefore subjected to high forces and, especially in the machining center, the non-stationary components are in continuous movement along different directions. The SPM has five ball screws (one in the table, one in each milling station and two in the drill-box), while the MC has only three (one in the table and two in the spindle); there are also five guideways in the SPM and three in the MC, placed in the same components as the ball screws; moreover, the SPM has one spindle in each milling station (one spindle makes two tools rotate) and two spindles in the drill-box.

It is important to underline that, not only the number of different components in each machine is relevant, but the type of component is very important to understand the maintenance that is needed for the machine. The SPM has box guideways or boxways: they give high friction and can be used at low feeds. However, they have the big advantage of having high damping. They need a periodic preventive maintenance called scraping: the slides of boxways have to be rubbed with scraping tools to obtain required geometry specifications. This techniques is done every year and makes it sure that the service life of the guideways (of course, of no other failure occurs) can last for the whole machine tool life. On the other hand, the machining center has linear guideways: they can stand high feeds, which is

---

<table>
<thead>
<tr>
<th>Component</th>
<th>SPM</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball screws (#)</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Guideways (#)</td>
<td>5 (box guideways)</td>
<td>3 (linear guideways)</td>
</tr>
<tr>
<td>Spindle (#)</td>
<td>4 (with gearbox, roller bearings)</td>
<td>1 (with gearbox, ball bearings)</td>
</tr>
</tbody>
</table>

Table 3.3: Number and type of components in SPM and MC

4Encoders and the machine bed are not taken into account in this case study.
good from a productivity point of view, but they have less damping and they usually have a much shorter lifespan than the box guideways.

### 3.3 Choice of critical machine tool and features

Since this study is part of a bigger project that takes into account the whole lines, some steps had to be followed in order to choose which machine to analyze in this work. This decision has been taken after a thorough study of the process plan for the cylinder block DC13 and with the help of production managers at Scania. Three steps have been followed, as it is shown in Figure 3.7.

![Figure 3.8: Steps to identify critical features](image)

First of all, the process plan was analyzed in order to find the critical operations\(^5\), in terms of machine tool concept choice. Indeed, some operations must be performed in a machining center since they change from one product variant to another and they require flexibility; for others, Scania experienced it was much more convenient to have a SPM, in order to have higher productivity and stiffer machines; some other operations could be, instead, performed with both machine tool concepts. These latters were defined as critical operations, to be further investigated. The second step was, indeed, the analysis of the critical operations.

Then, with the help of Scania production managers, the critical features have been chosen. Table 3.2 shows the chosen critical operation (called OP, which stands for operation) in the old line (OL) and in the new one (NL), its related cutting operations and the features machined in OP20; moreover,

\[^5\text{In this study the term “operation” should be referred as the set of cutting operations done in a station/machine. One operation might have one or more machines in parallel. If the word “operation” will be used to refer to a cutting or machining operation, this will be stated clearly.}\]
the last columns show the operation where the finishing is performed in the two lines that (for OP20 is still OP20).

<table>
<thead>
<tr>
<th>Critical operations OL</th>
<th>Critical operations NL</th>
<th>Cutting operation</th>
<th>Feature</th>
<th>Finishing OL</th>
<th>Finishing NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP20</td>
<td>OP20</td>
<td>Rough milling left side</td>
<td>500(1), 500(2)</td>
<td>OP20</td>
<td>OP20</td>
</tr>
<tr>
<td>OP20</td>
<td>OP20</td>
<td>Rough milling right side</td>
<td>3300(1), 3300(2)</td>
<td>OP20</td>
<td>OP20</td>
</tr>
</tbody>
</table>

Table 3.4: Critical features

These features are considered as critical since, although they do not have very tight tolerances, they are the primary datum for the cylinder-block: therefore, the accuracy in their production is crucial for the whole process plan in the cylinder-block production.
4. Modeling a machine tool selection

The selection of a machine tool and especially the choice between a special purpose machine and a machining center can be quite critical, considering the different advantages and drawbacks that the two concepts entail.

In the selection of a machine tool concept it is then important to evaluate which machine can fulfill the aforementioned goals of the machining system in the most efficient way. In order to do that, it can be helpful, as a decision support tool, to simulate the behavior of the system with different scenarios in both cases of using a machining center and a special purpose machine. As a consequence, the behavior of machining system performance indicators will change and each scenario will correspond to some machining system conditions and therefore to a machining strategy. However, the adoption of one machine tool concept or another is on itself a decision included in the machining strategy definition. In this way, it will be possible to evaluate which machining strategy is the best to employ. It can be also of interest to evaluate different policies that change the system structure and might improve the results.

The overall system comprising machine tool, process and machining system performances, with their all related variables will then be modeled and a framework to evaluate machining strategies will be shown. System Dynamics is the utilized modeling tool for this study. Among the
commercial software available for SD\(^6\), Stella/iThink has been chosen to build the model presented in this case study.

### 4.1 System Identification: CLD

The correct definition of the system and its boundaries is essential in order to make a reliable SD model. The whole system represented in this model comprises the machining system, its performance indicators and other cost, operational and maintenance-related parameters. The CLD will include only the most relevant variables for the dynamics of the system; the other parameters and their analytical relationships will be described in the S&F diagram section. It is worth to divide the model in three subsystems and therefore sub-models to better understand its structure and hence its behavior: machining system parameters, operational and maintenance subsystem and cost subsystem. As it will be shown, the three subsystems are related to each other and interact to create the total behavior.

Figure 4.1 displays the CLD. In the model, red variables are input variables\(^7\); blue variables are machining system parameters, green variables are operational parameters, black variables are maintenance-related parameters and purple variables are cost-related parameters.

The main input parameters are:

- Order rate [parts/month]: it is the monthly demand of cylinder-blocks, restricted to OP20.
- Takt [minutes/part]: it indicates how often the product should exit OP20 in order to fulfill the demand\(^8\) [26].
- Number of machines [unitless]: it is the number of machines in parallel for OP20.

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\(^6\) Stella/iThink, Prowersim, Vensim, Stella/iThink and AnyLogic.

\(^7\) The takt time is an exception since in the policy analysis it will not be considered as a constant anymore.

\(^8\) For OP20 it is intended the set of machines that perform the cutting operations of OP20, therefore if the takt time is \(X\) min/part and there are two machines in parallel the takt per each machine should be \(2\times X\) min/part.
- Time for preventive maintenance [minutes/month]: it is the time dedicated preventive maintenance in a month. This is actually planned per year; therefore it is calculated by dividing the yearly planned time for preventive maintenance divided by twelve.

Figure 4.1: CLD for the actual situation

Figure 4.1 shows that the number of machines influences the cycle time and capital cost, while in the S&F diagram it will be evident that it actually
influences also other variables\textsuperscript{9}. However, in order to have a clearer diagram, only these two variables are linked to it.

Machining system variables are:

- **Feed per tooth [mm/tooth]**: it is the distance traveled by each tooth of the cutting tool during one revolution.
- **Feed rate [mm/minute]**: it is the relative translational speed of the table and the spindle during face milling.
- **RPM [1/minute]**: it is the number of revolutions per minute done by the milling cutter.
- **Cutting speed [m/minute]**: it is the rate at which the cutting edge of the tool passes the uncut surface of the work piece.
- **Edge life [parts/edge]**: it is an indicator for the tool life. A tool is composed by a certain number of inserts and each insert can have two or more edges. Once an edge is worn out, the insert has to be re-indexed and a new edge is then used. Therefore, the edge life is the number of parts that an edge is able to machine with defined cutting condition.
- **Used tools [tools/month]**: it is the number of used tools per month\textsuperscript{10}.

Operational variables are:

- **Cycle time [minutes/part]**: it is the time between two different exits of a component from the OP20. It is therefore the required time to clamp, process (including all the cutting operations in OP20) and unclamp the part.
- **Backlog [parts]**: it is the number of components that have been ordered but not yet processed in OP20.
- **Throughput rate/Order fulfillment rate [parts/month]**: it is the number of parts that are produced by the machine tool in a month.
- **Desired production rate [parts/month]**: it is the number of parts that the production management wants to produce in a month in order

\textsuperscript{9}E.g. time for preventive maintenance, downtime for corrective maintenance, spare part cost, maintenance cost.

\textsuperscript{10}In the S&F diagram, this variable will be called “Used tools per month”.

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to fulfill the demand with an acceptable delivery delay and hence order backlog.

- **Uptime [minutes/month]:** it is the time in a month in which the machine is producing non-defective products.\(^{11}\)
- **Downtime [minutes/month]:** it is the time in a month in which the machine is not producing because of tool changing, planned or unplanned stops.
- **Capacity [parts/month]:** it is the number of components that OP20 can produce, considered the cycle time at which it produces and the available uptime.
- **Capacity GAP [parts/month]:** it is the difference between order rate and capacity.

The causal loop diagram also shows the main sources of cost and the consequent kind of cost that arises from them. Considering the system thinking approach, it is worth to model with a diagram – having the same notation as the causal loop diagram – the cost sub-system.

![Figure 4.2: System thinking diagram for cost sub-model](image)

\(^{11}\)In this case it is assumed that, considering the quality constraint to the variables, the number of defective products when the machine is producing is negligible.
From this, it is noticeable that the main considered costs are:

- Tool cost
- Capital cost
- Maintenance cost\(^{12}\), divided into:
  - Cost for preventive maintenance\(^{13}\) (operators and DynaMate staff)
  - Cost for corrective maintenance\(^{14}\) and scheduled overhaul\(^{15}\) (DynaMate staff)
- Overtime cost
- Spare part cost

Table 4.1 shows the types of cost that are taken into account in the model and the main sources that will cause these costs to arise or increase.

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>Sources of cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td>Number of machines and type of machine</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>Time chosen from preventive maintenance, downtime for corrective maintenance and scheduled overhaul</td>
</tr>
<tr>
<td>Tool cost</td>
<td>Number of used tools, which depends on tool life (and therefore on cutting speed) and on the throughput rate.</td>
</tr>
<tr>
<td>Overtime cost</td>
<td>Total production time (if it is higher than a certain threshold)</td>
</tr>
<tr>
<td>Spare part cost</td>
<td>Component wear and consequent substitution</td>
</tr>
</tbody>
</table>

\(^{12}\) Maintenance is “a combination of all technical, administrative and managerial actions during the live cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [27]

\(^{13}\) Preventive maintenance is the set of activities performed to prevent failures in the machine components,

\(^{14}\) Corrective maintenance is done to intervene after a failure occurs.

\(^{15}\) Scheduled overhaul is a kind of preventive maintenance consists in the removal of equipment after a pre-set time before failure. In the CLD it is not specified because the software allows a maximum number of words to name each variable.
It is very important to know which are the sources of costs in order to understand the dynamics of the system and if the loops are desirable or not. They will be considered in the following section within the description of the feedback loops in the system.

4.1.1 Balancing and reinforcing loops

This section will illustrate the main loops present in the CLD. It is worth to point out that in the majority of the loops, the order rate and the throughput rate will be taken into account. This might seem to contrast with the scope of the model, which is related to machining strategies. However, the main goal of a machining system is to fulfill the demand in the required time, by producing products that meet the required tolerances and in an efficient way, which means at the highest productivity and lowest cost possible. Therefore, the order rate will be an input to the whole system that will change the performance targets and this will affect the machining system. In turn, decisions on the machining system will influence directly and indirectly machining system performances. This means, the two aspects are closely related to each other. Moreover, in this case study, decisions on the machining system are limited by the quality constraint and therefore they will be mainly related to adjustments of cutting parameters to meet productivity requirements.

Figure 4.1 shows that the system contains five main loops: four balancing and one reinforcing loop.

4.1.1.1 Balancing loop 1

This loop (Figure 4.3) shows that, if the order rate increases, an increment of the backlog will require a growth of the desired production rate in order to fulfill the demand. Therefore, if there is enough capacity, there will be an increment of the throughout rate and eventually a reduction of the backlog. On the other hand, if the order rate decreases, the reduction of the throughput rate will be limited.
It is worth to think that (in case of growing demand) this loop is activated only if the desired production rate is lower than the capacity. Otherwise, the production start rate will coincide with the capacity and remain constant. Therefore, this balancing loop is desirable if the capacity is higher or equal to the desired production rate since it will allow the company to fulfill the demand with a limited backlog. If the number of machines is increased, both capacity and throughput rate will grow and it will be beneficial since it will allow to fulfill the demand easily. However, this decision will provide higher capital costs.

### 4.1.1.2 Balancing loop 2

The balancing loop shown in Figure 4.4 is based on the decision of increasing or decreasing the production time in order to decrease the gap
between order rate and capacity, which means to permit the fulfillment of demand. It shows that, if the order rate increases, the growth of the capacity gap will be limited by an increment of the uptime. However – since the uptime will be calculated as the difference between total production time and downtime – this is true only if the downtime does not increase more than the total production time. If this condition is respected, the loop is beneficial to the system.

4.1.1.3 Reinforcing loop 1
This reinforcing loop (Figure 4.5) is also based on adjusting the production time to meet the demand.

![Diagram of reinforcing loop 1](image)

**Figure 4.5: Reinforcing loop 1**

In this case, however, if the order rate increases, the total production time needed to fill the gap can get higher than a certain threshold value, which means that OP20 must produce even during Saturdays. This will imply that the amount of preventive maintenance that usually is done during Saturdays, when the machine is not working, will become downtime, thus decreasing the uptime and the capacity. This will in the end increase the gap even more. This means that, if the total production time is increased
over a certain threshold, this loop will badly contribute to the productivity performance. Moreover, the overtime cost will be increased, together with maintenance cost.

4.1.2.4 Balancing loop 3

This balancing loop shows that a growth of throughput rate will cause an increase of the amount of tools that need to be used in order to mill all the parts.

Figure 4.6: Balancing loop 3

This means more time spent for tool changing, which will in turn increase the downtime and decrease the uptime. This will reduce the capacity that will eventually cause a drop of the production rate. An increment of tool life, which depends on the cutting parameters would damp the effect of this loop.
4.1.2.5 Balancing loop 4

This balancing loop is a control for the feed rate. Indeed, if the cycle time needs to be increased or decreased, the feed will grow or be reduced respectively, thus having the desired effect on the cycle time.

![Diagram of Balancing loop 4](image)

Figure 4.7: Balancing loop 4

4.2 SD modeling – stock and flow diagram

The stock and flow diagram shows the accumulation processes that take place in the system and cause its dynamic behavior.

Although the structure of the system for the SPM and MC are almost the same, it is worth to have two separate models, one for each machine concept in order to be able to simulate them separately. However, since – except for numerical values – they have many equal parts, the machining center model will be now described, while the special purpose machine one will be shown in the appendix. As for the different parts in the two models, they will be both explained in this section. Due to the big size of the model and in order to give a clearer explanation, also in this case it will be divided in the three parts: machining system, operational and maintenance and cost.

In this paragraph, the model described the current situation will be shown. The most important equations will be shown here, while the others are listed in the appendix. The other models representing the policies that will
be evaluated and that correspond to other machining strategies will be described in paragraph 4.3. This model needs to be tested in order to be validated: these results will be presented in Chapter 5.

4.2.1 Machining systems sub-model

In the actual situation, machining system input variables are:

- Setup time [minutes/part]: it is the time to clamp, position and unclamp the part in the machine. It is assumed that this time is constant and cannot be changed to increase or reduce the cycle time.
- Time for other operations [minutes/part]: it is the time required to perform the other machining operations (drilling) in the same machine tool. It is assumed that this time is constant and cannot be changed to increase or reduce the cycle time.
- Inserts [tooth]: it is the number of inserts in a milling tool.
- Tool diameter [mm]: it is the diameter of each milling tool.
- Machining time [minutes/part]: it is the time to perform the milling of the two lateral faces of the cylinder block. Of course, it depends on the used feed rate and on the amount of material to be removed. The higher the machining time is, the higher the cycle time will be.

The full SD model of the machining system parameters can be found in the appendix. Since the sub-model is quite large, this part of the model will be divided in three parts.

The first part (Figure 4.8) is the one more on the left and shows the control loop aiming at adjusting the cycle time with respect to the takt time. In order to settle the machining parameters, some tests are run to actually measure the cycle time and set the parameters. Therefore, in the model, the stock “Cycle time” (CT) is perceived with an information delay due to this number of tests in order to decide the cutting parameters setup. The structure is an information delay is a kind of smoothing of the actual value of cycle time (“Actual cycle time”, in the model). Anyway, being the delay time quite short (0.25 months) the “Cycle time” will be a quite good approximation of the “Actual cycle time” (CT_{actual}).
Variables are calculated as follows:

\[ CT = \int_{0}^{1} \text{Change}CT(t) \cdot dt + CT^{\text{init}} \]

Where:

CT [min/part] – Cycle time

\( \text{Change}CT(t) = \frac{CT_{\text{actual}}(t) - CT(t)}{\text{delay time}} \) – Flow rate of cycle time. It is a biflow, signed with the double arrow, which means that it can be positive or negative\(^{16}\).

CT\(^{\text{init}} \) [min/part] – initial value of the stock (6 minutes).

The actual cycle time depends on the time spent for the different cutting operations in OP20, for the setup and on the number of machines in parallel. It is calculated with the formula:

\[ CT_{\text{actual}} = \frac{MT_{\text{Roughing}} + MT_{\text{Finishing}} + T_{\text{Setup}} + T_{\text{Other}}}{\text{Number of machines}} \]

\(^{16}\)A positive or negative rate makes cycle time increase or decrease respectively.
Where:

$MT_{\text{Roughing}}$ [min/part] – machining time for rough milling of the four features

$MT_{\text{Finishing}}$ [min/part] – machining time for finish milling of the four features

$T_{\text{setup}}$ [min/part] – setup time

$T_{\text{other}}$ [min/part] – time for the other cutting operations in OP20

The variable “Machining Time” is an array-variable (how it can be seen in Figure 4.8 it has a 3D-shape). This means that it can have one or two dimensions with two or more rows per each dimension (color). In this case, it has only one dimension, which is called “Process”: this dimension has two levels/rows, which are “Roughing” and “Finishing”. The combination dimension-level is associated to a value or equation that can be independent from the others, as it is in this case.

The time ratio is calculated as Cycle Time/Takt. Therefore, if it is higher than one, it means that the machine is producing slower than it should; if it is lower than one it is faster. For sure, this ratio should not be higher than one. However, although it could be though that the best solution would be
to have it as low as possible, this is not true. Indeed, a reduction of feed rate would allow a lower cutting speed and eventually less

Since the quality of the product must be a constraint that must not be neglected, there are two measures that are taken in the model:

1. A maximum value for the feed rate is considered as a constraint.
2. If the cycle time is lower than the takt time, the control loop will make sure that the feed rate will be lowered down so as to achieve better surface quality.

The control is based on the variable “Effect of cycle time on feed rate”, which is a graphical function of the time ratio, used as a multiplier to the maximum feed rate. When the ratio increases, the variable “Effect of cycle time on feed rate” and feed rate have to increase as well.

The limits of the time ratio are based on the assumption that the cycle time should not be more than 20% higher than the takt time and can be around 50% lower than it.
The feed rate \( f_r \) will be then:

\[
f_r = f_{r_{MAX}} \cdot \text{Effect of CT on Feed Rate}
\]

\( f_{r_{MAX}} \) – maximum feed rate. In this model it is the value that is currently used in the company.

The range for the variable “Effect of Cycle Time on Feed Rate” – and the function itself – changes from one cutting operation to the other, since the limits for feed rate change with the cutting operation. The feed rate is, in fact, a one-dimension array variable with the two levels of process Roughing and Finishing. The minimum feed rate is calculated from the minimum cutting speed that can be taken in the process. The number of data points is taken in order to have a stable feed rate for small oscillations of the cycle time\(^\text{17}\).

In the case of feed rate for finishing operations, the graphical function is actually set constant to 1. This choice is due to the fact that, while roughing operations are used to increase productivity and reduce costs, finishing processes have to ensure the final quality. Since this constraint cannot be compromised and since exact ranges that would ensure the required quality were not available.

The calculated feed rate will then feed back to the machining time which is calculated through the formula:

\[
T_{\text{machining}} = \frac{\text{mm\_per\_part}}{f_r}
\]

\text{mm\_per\_part} is a variable that indicates the length that has to be milled on the work piece.

Considering the SPM case this is actually true, since the tool is big enough to remove all the material by passing once only on the surface that has to be machined. On the other hand, the machining center is not so robust to stand

\(^\text{17}\)If the number of data points is too low, the control is not effective; on the other hand if the number is too high, a small oscillation of cycle time and hence of time ratio will give changes in feed rate, which is not realistic.
the forces of such big tools. Therefore, it has to pass more times to machine the whole face and the constant “mm per part” should then be an approximation of the total path of the tool on the surface. Anyway, in both case, this parameter was determined in the reverse way as the product between the actual machining time and the actually used feed rate.

The second part of this subsystem (Figure 4.10) shows the relationships between feed rate and RPM and between RPM and cutting speed. It is described a control on the RPM – which is an array variable, with the two levels of Roughing and Finishing – in order to have a desired feed per tooth and therefore control the cutting force\(^{18}\). However, this value is limited by the constant “Max RPM” (maximum RPM) which is in turn limited by a maximum value for the cutting speed, used to limit the tool wear.

![Figure 4.10: Machining system sub-model – Part II](image)

The main formulas used in this part of the model are those that follow.

\[
\text{Desired}_\text{RPM} = \frac{f_r}{\text{Desired}_{f_z} \cdot z}
\]

---

\(^{18}\) The cutting force is proportional to the chip thickness which is in turn proportional to the feed per tooth.
Where

Desired$_{f_z}$ [mm/tooth] – desired feed per tooth

$z$ [tooth] – number of inserts in the tool

$$Change\_in\_RPM = \frac{\min(Desired_{RPM}, RPM_{MAX}) - RPM}{Time\_to\_change\_RPM}$$

This means that if the RPM reaches its maximum allowed value, it will not be increased anymore.

$$V_c = \frac{RPM \cdot 2\pi D}{Conversion\_factor\_mm\_to\_m}$$

Where

$V_c$ [m/min] – cutting speed

$D$ [mm] – tool diameter

Conversion factor mm to m [mm/m] – this constant (1000 mm/m) is specified as a separate converter for dimensional constraints in the model.

The last part of this subsystem shows the relationship between cutting speed and tool life (Figure 4.11)

![Machining system sub-model](image)

**Figure 4.11: Machining system sub-model – Part III**
In this case, instead of “tool life”, the variable is called “Edge life” (the explanation can be found in the previous section, where the variables present in the CLD were explained)

The edge life is calculated with a multiplier, which is the variable “Effect of cutting speed on edge life”.

This variable is based on the assumption – taken from discussion with experts in the company – that the tool life will increase by 60% for every reduction of 10m/min of the cutting speed. This graphic function depends on the ratio Cutting speed/Minimum cutting speed. The higher the ratio is, the lower the edge life will be.

Edge life is then calculated as:

\[
\text{Edge\_Life} = \text{Effect\_of\_cutting\_speed\_on\_edge\_life} \cdot \text{Min\_edge\_life}
\]

Limits for cutting speed are settled and steps of 10m/min from the minimum to the maximum level are taken into account.

![Figure 4.12: Effect of cutting speed on edge life](image-url)
4.2.1.1 Differences with special purpose machine

In the actual situation, the special purpose machine has four spindles with a constant RPM. Since this cannot be changed, the second part of the model for this subsystem is different (Figure 4.13).

![Figure 4.13: RPM in SPM model](image)

The feed per tooth is calculated as:

\[ f_z = \frac{f_r}{RPM \cdot z} \]

4.2.2 Operational and maintenance sub-model

- Time to change component (guideways, spindle bearings and ball screws) [months]: it is the needed time to substitute a worn out machine component.
- Number of components (guideways, spindle bearings and ball screws) [unitless]: it is the number of components of each kind present in one machine.
- Wear threshold component (guideways, spindle bearings and ball screws) [unitless]: it is the maximum value of component wear after which a component substitution is necessary.

This part of the model (see the appendix) shows the main dynamics within the productivity and maintenance system. Also in this case, it is better to
divide this subsystem in more parts, in order to describe it in a more detailed and clear way.

4.2.2.1 Operational variables

The operational variables are mainly linked with productivity performance. This part of the system is modeled as a normal production system, but with only one machine.

Figure 4.14: Operational sub-model

Indeed, first of all, the order rate is considered. As it was mentioned before, it is an input and will cause an accumulation of not-yet delivered parts (backlog). This stock is emptied by an outflow which is, indeed, the order fulfillment rate. From a numerical point of view, this outflow is equal to the throughput rate.
Figure 4.15: Operational sub-model – Part I

This feedback loop (Figure 4.15) is based on the assumption that the company will accept some delay between the arrival of the order and the moment in which it is decided to machine that product in OP20. Considering the backlog and the desired delivery delay, the desired production rate will be:

\[ X_{\text{des}} = \frac{B}{\text{Del}_{\text{des}}} \]

Where:
- \( X_{\text{des}} \) – desired production rate or desired throughput
- \( B \) – Backlog
- \( \text{Del}_{\text{des}} \) – desired delivery delay
On the other hand, it will not be possible to machine any amount of product: in fact, this number is limited by the capacity of the machine over a certain period of time. The latter is calculated as

\[ \text{Capacity} = \frac{\text{Uptime}}{CT} \]

The production start rate \((X_{\text{start}})\), which is the amount of product that it has been decided to be produced based on capacity constraints and the desired production rate, will be:

\[ X_{\text{start}} = \min\{\text{Capacity}; X_{\text{des}}\} \]

This will be an inflow to the WIP\(^{19}\), which is a stock that takes into account the amount of products that can be produced in OP20 but that are not been processed yet.

The outflow to the WIP will be, indeed the throughput rate \((X)\), which, for the Little’s law, will be calculated with the formula:

\[ X = \frac{WIP}{CT} \]

The cycle time has to be actually divided by the conversion factor minutes to month with the unit \([\text{minutes}^\text{part/month}]\). The throughput rate will then feedback to the order fulfillment rate and thus to the backlog, which will be reduced subsequently.

Taking into account what has been described until now, there is the possibility that the capacity is lower than the desired production rate and that it will therefore be impossible to fulfill the demand. In order to avoid

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\(^{19}\)Although the machine tool can have only one work in process per time, the WIP can be higher than one part since the DT counts every 0.02 months which is roughly every two working shifts and in this time window the number of processed part is of course higher than one.
this problem, a control to the total available time to produce (“Total production time” stock) is currently implemented (Figure 4.16).

Figure 4.16: Operational sub-model – Part II

As it was previously defined, the “Capacity GAP” is the different between the order rate and the capacity.

Considering a constant takt time, the desired total production time, needed to fulfill the demand will be:

\[
ProdTime_{\text{desired}} = \text{ProdTime}_{\text{actual}} + \text{CapacityGAP} \cdot \text{Takt}
\]

This means that the desired total production time (ProdTime\text{Desired}) will be the total production time (ProdTime\text{Actual}), which is the stock in Figure 4.16, plus the time to produce the amount of products of the capacity GAP. Of course, if the capacity is higher than the order rate the GAP will be negative and the total production time will be reduced so as to be able to produce the ordered amount of products.

Having defined the desired production time, the total production time will be adjusted with a balancing loop (goal seeking behavior), changed with the biflow “Change in tot prod time”, which is calculated with the formula:

\[
ProdTime_{\text{change}} = \frac{\min(ProdTime_{\text{desired}}, \text{ProdTime}_{\text{max}}) - \text{ProdTime}_{\text{actual}}}{\text{Time to change time}}
\]
The maximum total production time (Max_Tot_Prod_Time) is the maximum available time to produce (in minutes/month) – confidential value for the company.

The variable “Time to change time” is the number of months needed to adjust the total production time.

Therefore, the equation to calculate “Change in tot prod time” has the same structure as formula for the variable “Change in RPM” and means that the total production time will increase or decrease with a proportional rate to the minimum value between the desired and the maximum production time minus the actual production time. Therefore, if the total production time reaches the maximum production time value, it will not be increased anymore.

The total production time will then influence the uptime, which is equal to:

\[ Uptime = ProdTime_{Actual} - Downtime \]

4.2.2.2 Maintenance variables

It has been already pointed out that the total downtime is the sum of downtime for tool changing, downtime for corrective maintenance and components overhaul and downtime for preventive maintenance (excluded scheduled overhaul).

- Preventive maintenance

The time spent for preventive maintenance is divided into activities that are usually performed during working days and others done in the weekends. Therefore, a part of the time for preventive maintenance will not be counted as downtime. It will become downtime if the total production time goes beyond a certain threshold, (Confidential value): this means that even in the weekend – at least during Saturdays – the machines are working and the shutdown for preventive maintenance activities will be downtime for production.
The time for preventive maintenance is calculated based on the policies for the old line, as follows.

In total, there are four hours per week of scheduled stop for preventive maintenance performed by the operators in the line. This means that in one month, considering a total amount of four weeks per month, there will be a total amount of XXX hours (confidential) of planned stop per month. The
old line has XXX (confidential) special purpose machines. If all special purpose machines need the same time for preventive maintenance, then the planned downtime for preventive maintenance performed per month by operators in OP20 in the old line is:

Moreover, in OP20, the operators need to shut the machine down for a certain number of hours (confidential) every week.

Moreover, the DynaMate staff performs the following preventive maintenance activities once a year:
- Check the backlash in ball screws
- Check the play in ball screws
- Scraping for the box guideways
- Visual control of the machine tool

This work is, however, made during weekends: therefore it is not usually counted as downtime, since the machine is not supposed to work. Total estimated time for these activities is confidential information. Other time is usually spent for other preventive maintenance activities, like changing cutting fluids and renovating electrical system.

Therefore – on average – the total time for preventive maintenance per month for a special purpose machine is:

- Corrective maintenance and scheduled overhaul
The corrective maintenance and scheduled overhaul variables are mainly related to the substitution after the end the components service life and to the failures that can occur as a reduction of service life caused by a lack of needed preventive maintenance.

As it was mentioned in chapter 3, three main machine tool components that are taken into account are spindle bearings, guideways and ball screws. For each of them, the wear is a stock that accumulates at a certain wear rate. In a certain period of time (which is the lifespan or service life of the component) the stock will reach a threshold value, after which the scheduled overhaul has to take place.

From interviews to DynaMate professionals, it has been concluded that a decrease of time for preventive maintenance will lead to failures or problems on the components that need for corrective maintenance for component substitution before the lifespan of the component is expired. In order to unify these two situations, a variable called “time to wear” has been introduced and this will directly depend on the time for preventive maintenance. This behavior is represented with a graphic function (Figure 4.18).

![Figure 4.18: Time to wear of a component depending on time for preventive maintenance](image)
When the time for maintenance is maximum, then the time to wear will coincide with the service life of the component and the maintenance activity will be the scheduled overhaul; if the time for preventive maintenance is less than the maximum, then the time to wear is shorter (the value is an assumption, because there is no way to predict failures without monitoring the component) and the maintenance activity will be corrective and will consist in the substitution of the component.

The maximum value for the time for preventive maintenance is set as already described, while the minimum value is zero. The whole preventive maintenance time is taken into account as independent variable since it is assumed that if the policy of having preventive maintenance is adopted, then it will be taken for all the components. This limitation is due to the fact that the evaluation of the total preventive maintenance time and of the time to wear starting from the preventive maintenance of the single components was not feasible.

The component substitution is represented as an outflow that will empty the wear stock within a time that is the needed time to do the overhaul. While the substitution is being performed, a certain downtime and cost are allocated. The total time for corrective maintenance is then the sum of the downtime for the three components overhaul.

In the modeling of this part, the following assumption has been made: the different components of the same type in one machine tool wear out at the same pace and they are substituted at the same time. This is because the majority of failures are not predictable without monitoring some variables with condition-based maintenance methods. Therefore, it was not possible to differentiate the wear of two components in one machine tool.

The cost of these components as spare parts has not been provided by the company, but has been taken from an SKF catalogue [28]. The time to change the components have been assumed or derived from interviews to DynaMate personnel.
4.2.2.3 Differences with special purpose machine

As it was described in chapter 3, maintenance is not needed by all the machine tool components. In particular, linear guideways that are in the MC do not need any preventive maintenance. Instead, the special purpose machine has box guideways, which need yearly preventive maintenance.

If these activities are not performed, the service life of box guideways can be extremely reduced. For this reason, while in the machining center model, the time to wear for guideways is a constant, in the SPM one it depends on the time for preventive maintenance (Figure 4.19).

![Figure 4.19: Maintenance sub-model SPM](image)

Moreover, the model of the SPM considers all the components of the machine tool, even though they are used for drilling operations (there is one spindle that works exclusively for these other cutting operations). This is because the machining center has a more compact structure and uses the same spindle to machine all the features of the part. Therefore, in order to make a more reasonable comparison of the costs for corrective maintenance, the whole workload for both machines had to be considered and thus even the spindles, guideways and ball screws that are not used for the face milling operations.
4.2.3 Cost sub-model

This sub-model is an output of the rest of the model. It includes the main costs derived by the choice of one machining strategy. The model is shown in Figure 4.20.

![Figure 4.20: Cost sub-model](image)

The variable “Actual cost per part” is calculated as:

\[
\text{Cost}_{\text{Capital}p} + \text{Cost}_{\text{Tool}p} + \text{Cost}_{\text{SparePart}p} + \text{Cost}_{\text{Overtime}p} + \text{Cost}_{\text{Maintenance}p}
\]

where:

Cost\(_{\text{Capital}p}\) – capital cost per part, which takes into account the machine tool cost during its service life of fifteen years\(^\text{20}\)

\(^{20}\)The interest rate is not taken into account, being the same for the two machines, since then it would not bring any difference between the two concepts.
Cost\textsubscript{Toolp} – tool cost per part, which is the cost of the used tools in each machine\textsuperscript{21}
Cost\textsubscript{SparePartp} – spare part cost per part, which is the cost of the new machine tool components that have to be bought to substitute the parts that are worn out or that have finished their service life.
Cost\textsubscript{Overtimep} – overtime cost per part, which is the cost to pay operators that work overtime.
Cost\textsubscript{Maintenancelp} – maintenance cost per part, which is the cost for operators and DynaMate staff paid for preventive and corrective maintenance activities.

All the variables “cost per part” are calculated as a cost divided by the throughput rate plus 0.01\textsuperscript{22} and have the unit of measure SEK/part.

The cost variables are derived as follows.

- Capital cost per part
  The total purchasing cost for one machine is multiplied by the number of machines and divided by the service life of a machine, which is 15 years\textsuperscript{23}. It is then divided by a conversion factor to obtain the monthly cost and eventually by the throughput rate plus 0.01.

- Tool cost per part
  This is calculated by multiplying the price per tool by the number of used tools per month and then dividing it by the throughput rate plus 0.01. However, the price per tool is calculated in two different ways for machining center and SPM.

\textsuperscript{21}The cost for refurbishing tools, which would lower of a certain amount the tool cost, is not taken into account since it is assumed that once the tool is worn out it is exchanged with a new one.
\textsuperscript{22}This constant is added in order to better fit the model with the reality, since it could happen that the throughput is zero and the simulation would return infinite cost value, which is not reasonable.
\textsuperscript{23}To simplify the model, the interest rate us not taken into account since it is the same for all the machines.
In the former case, the tool price is:

\[ \text{Price}_{tool} = \text{Insert price} \cdot \text{number of inserts per tool} \]

For the SPM, instead, the presence of wiper inserts in the tools has to be considered. It is shown in Figure 4.21. A new array dimension called “Insert type” has been created: it has two levels, “normal” and “wiper”. The variable “Inserts considering wipers” is a two-dimensional array with – as columns – different tools and insert types. The combination “tool-insert type” indicates the number of inserts of each type in each tool.

![Diagram](image)

**Figure 4.21: Tool cost in SPM**

The variable “Insert price” has the same structure as “Inserts considering wipers” and shows the price of each type of insert in each tool. Then, the price per tool is an array variable with one dimension (tool) calculated as:

\[ \text{Price}_i = \text{Price}_{i_{\text{Normal}}} \cdot \text{Number}_{i_{\text{Normal}}} + \text{Price}_{i_{\text{Wiper}}} \cdot \text{Number}_{i_{\text{Wiper}}} \]

Where the subscript \( i \) indicates the tool taken into account.

- Spare part cost per part
This is the sum of the costs to substitute the components, divided by the throughput rate plus 0.01. The structure is shown in Figure 4.22.

![Figure 4.22: Spare part cost](image)

- **Overtime cost per part**
  The overtime cost per part arises only if the machine works for more than 21 days per month. If it happens, the cost will be of 322 SEK/hour (5.37SEK/min) multiplied by the number of extra-minutes in which the machine works.

- **Maintenance cost per part**
  It includes the operators and DynaMate staff cost for corrective maintenance, scheduled overhaul and preventive maintenance. One operator and one person from DynaMate are considered in the calculations.

DynaMate staff is paid XX SEK/hour, which is xx SEK/min. The considered operator cost for one year is ZZ SEK/year, which means (working 228 days/year, 24 hours a day) zz SEK/min.

The corrective maintenance and scheduled overhaul are considered as entirely performed by DynaMate staff. For the preventive maintenance instead, only the 40% is done by operators.

The maintenance cost [SEK/month] is then:

\[ xx \cdot (0.6 \cdot Time_{premaint} + Time_{corrMaint&Sch}) + zz \cdot (0.4 \cdot Time_{premaint}) \]
This is then divided by the throughput rate plus 0.01, in order to calculate the cost per part.

4.3 Policy design

In SD, policy design answers the following questions: “What new decision rules, strategies might be tried in the real world? How can be represented in the model?” [15]. Of course, these policies will be aimed at improving the system behavior: as a consequence, it is worth to first point out the main criticalities and points in which the system should improve.

Keeping in mind the description of the system done in paragraphs 4.1 and 4.2, some problems arise in the actual situation:

- If the order rate needs to be fulfilled a total production time higher than a certain threshold, the loop in Figure 4.5 will be activated and the capacity GAP will grow.
- When the total production time reaches its maximum value, if the demand increases, this cannot be fulfilled anymore.
- If the demand decreases, the cost per part gets very high and there is no loop that reduces it from the actual situation.

To overcome these problems, three main policies are proposed and tested.
1. After the total production time gets higher than the threshold that would increase the downtime, also the takt time is reduced to meet the demand.
2. If the needed total production time to fulfill the order rate is higher than the threshold that would increase the downtime, only the takt time is adjusted: this means that the total production time will never be higher than the threshold value.
3. Only the takt time is changed to meet the demand. This case copes with a scenario in which the demand is lower than the actual.
4.3.1 CLD after policy measures

The first proposed policy will change the system in a different way from the second and third. Now, the main loops arising from the policy measures will be described.

4.3.1.1 Loops from policy 1

Four loops are added to the system: two balancing and two reinforcing loops. They are shown in Figure 4.23.

![Figure 4.23: Loops in policy 1](image)

The first reinforcing loop includes only the takt and the total production time. It shows that an increase in takt time will cause a growth in total production time to maintain production, which will make the takt time grow even more. This loop is limited by the maximum production time in the first policy, where, then the takt will grow only thank to the desired production rate.

The second reinforcing loop (Figure 4.24) indicates that if the order rate increases capacity gap gets bigger and the total production time has to increase as well, since there will be the need of producing more to meet the
demand that will make the takt and then the cycle time higher as well. An increment of cycle time will in turn decrease the capacity that will eventually feed back to the capacity gap that will increase even more.

![Figure 4.24: Reinforcing loops in Policy 1](image)

However, this loop is limited by the balancing loop in Figure 4.25.

![Figure 4.25: Balancing loop 1 in Policy 1](image)
With this balancing loop, when the order rate increases, a growth in backlog will make the desired production rate increase and, if the total production time increases and gets higher than the threshold, there will be the possibility to decrease the takt time and therefore increase the cutting parameters and thus reducing the cycle time. A decrease in cycle time will increase the throughput rate and limit the backlog.

The last balancing loop is displayed in Figure 4.26.

Figure 4.26: Balancing loop 2 in Policy 1

This loop has the same effect as the previous but it shows also the effect of cycle time on capacity and in turn the effect of capacity on the throughput rate.

4.3.1.2 Loops from policies 2 and 3

The two reinforcing loops, in policies 2 and 3 will not exist anymore. The resulting CLD is illustrated in Figure 4.27.

From a productivity perspective, if the loop in Figure 4.5 is considered, the advantage will be of limiting the downtime for preventive maintenance and therefore the loop will not be activated.
In the case of policy 3, another big advantage is brought in terms of cost: if the order rate decreases, the balancing loops will make the takt longer and therefore the feed rate and the other cutting parameters will be reduced, thus decreasing the tool cost and limiting the increment of the total cost per part. This will be shown in the next chapter with the results.

4.3.2 S&F diagram after policy measures

The S&F diagram is the same as the one described in paragraph 4.2. However, there are two main changes:

- The models for SPM and MC are unified through array variables. A new array dimension called “Machine tool” has been created with two levels, “SPM” and “MC”.
- The operational sub-model, where the control on the total production time is displayed is different from one policy to the other and will be described in the next section.
4.3.2.1 S&F diagram for Policy 1: Adjustable takt time

This policy is tested on the actual situation. If the policy is activated, the takt will not be a constant anymore, but a control loop on it will be set.

Figure 4.28: S&F diagram Policy 1

The takt will then be a stock that depends on a biflow called “Change in takt time” calculated as:

\[
Change \text{ in } \text{takt} = \frac{Desired \text{ takt} - Takt}{Time \text{ to change } \text{takt}}
\]

The desired Takt is calculated with the formula:

\[
if \ (Tot_{prodt ime} \leq Time_{threshold}) then (init(Takt)) else \left( \frac{Desired_{tot \ prod \ time}}{Desired_{production \ rate}} \right)
\]

This means that – if the policy is active – as soon as the total production time gets higher than the threshold that would make OP20 work even during weekends, thus increasing the downtime, with a certain delay (set as one month) the takt will be adjusted. Otherwise, the takt is set as at its initial value. The total production time always depends on the takt.
4.3.2.2 S&F diagram for Policy 2

This policy is tested with a basic scenario in which the Total production time has as its maximum value the time threshold to work in the weekends. Therefore, if the police is not active, the maximum production time will be of 21 days/month and the takt will be fixed.

When the police is active,

\[ \text{if} \left( \frac{\text{Desired tot prod time}}{\text{Time threshold}} \leq \frac{\text{Desired tot prod time}}{\text{Desired prod rate}} \right) \text{then} \left( \frac{\text{init}(\text{Takt})}{\text{Desired prod rate}} \right) \text{else} \left( \frac{\text{Desired tot prod time}}{\text{Desired prod rate}} \right) \]

The adjustment of takt is the same as in the first policy with the only difference that in this policy, the condition is based on the fact that the desired total production time is higher than threshold, since anyway, the total production time will never get higher than that.

4.3.2.3 S&F diagram for Policy 3

The last policy (Figure 4.30) is tested the actual scenario and it is based on adjusting only the takt when the demand is lower than the actual.
The simulation is run with a lower order rate than the other policies (Figure 4.31). Numerical values are confidential.

When the policy is active, the total production time will only be a stock with no flow and the takt will be a stock with the same flow as the first two policies. The desired takt will be instead changes and calculated as the ratio between total production time and desired production rate.

4.3.3 Other proposed changes

A variable RPM for the special purpose machine should be taken into account. The currently used machine tool is, indeed, from the early ‘90s
and has a fixed RPM. This would now be quite obsolete and, should a company buy a SPM, the spindles would have changeable RPM. The structure in the model is the same as the one for the machining center see appendix. This policy is kept for all the already described policy models.
5. Results

In this chapter, the results of the simulations for the above described models will be presented. A comparison between the different policies and between the two machine tool concepts will be shown and considerations on future work will be underlined.

5.1 Base scenarios

The scenario specification answers to the questions: “What environmental conditions might arise?” [15]. Therefore, the different scenarios are based on the variation of some input variables. For the actual situation, some parameters that could be changed in the case of the machining center must be fixed for the SPM: the scenarios for the two machine tool concepts will be therefore differentiated.

Before simulating the model with different scenarios, however, the model should be validated. In order to do that, three simulation runs are performed in three cases: a constant demand, comparable to the actual and two extreme situations of very low and very high order rates.

- Base scenarios 1-2
  In the first scenario, the order rate is increasing in three steps. The numerical values are confidential data from the company and are not put in the public report. The second scenario presents the same steps but starting from the highest and finishing with the lowest.
Figure 5.1: Order rate for base scenario 1

For the second demand type see appendix. The other parameters are set as:

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>SPM</th>
<th>Machining Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Machines [unitless]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Time for preventive maintenance [minutes/month]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum cutting speed [m/min]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Parameters in base scenarios 1 and 2

- Base scenario 3
  The number of machining centers will be increased to 3.

- Base scenario 4
The time for preventive maintenance will be halved.

- Base scenario 5
  The time for preventive maintenance will be set to zero.

## 5.2 Simulation results

All the simulations were run with the same specifications of:
- $dt=0.02\text{months}^{24}$
- Running time = 180 months

Results will be divided in two main parts: actual situation and policy making. Both of them will be tested with different scenarios that will be now described. Afterwards, the results with the actual situation and with the proposed policies will be compared.

### 5.2.1 Testing results

The results from the tests with the constant actual demand and in the two extreme conditions validate the model. They show the actually used cutting parameters and they confirm the foreseen limits in demand fulfillment and the expected system behavior. Validation results can be found in the appendix.

### 5.2.2 Results for the actual situation

The results for the model of the actual situation, with the five scenarios will be shown.

#### 5.2.2.1 Actual situation – Base scenarios 1-2

Considering the actual situation, the model shows that the demand can be fulfilled under a certain maximum level that corresponds to the maximum production time.

---

24The $dt$ has been chosen as shorter than the shortest delay variable which is 0.03 months
However, since the cycle time for the special purpose machine is lower than the one of the machining center, the maximum demand that can be fulfilled with that fixed takt for the machining center is lower than that of the SPM. For both the machine tool concepts, it is necessary to produce over the threshold that indicates the maximum regular time for production: therefore, all the time dedicated to preventive maintenance will be downtime and the loop in Figure 4.5 will be activated.

As for the cost per part, since two machining centers are required, while only one SPM is kept, it will be higher in the case of machining center, because of high investment costs, maintenance costs and even tool costs per part. The cost per part (Figure 5.3) will be decreased in the last periods since the throughput will be higher.

![Figure 5.2: Order rate (blue), Throughput rate for SPM (red) and for MC (purple) in base scenario 1](image)

However, it can be noticed that, despite the throughput will grow between the second and third phase (before month 135), the cost will not further decrease: this is due to the higher cost for overtime and of downtime for preventive maintenance because the total production time is higher than the time threshold. The plots of the other costs are shown in the appendix.
Figure 5.3: Perceived cost per part for SPM (blue) and MC (red) in base scenario 1

The peaks showing a drop of productivity and a tremendous increase in cost per part, in Figure 5.3, are due to the components substitution (see plots in appendix). Indeed, while the corrective maintenance or component overhaul is done, the throughput will drop and the cost for spare parts and for personnel dedicated to maintenance will be very high. As a consequence, the throughput rate will tend to zero and the cost per part will be very high.

Figure 5.4 is a zoom showing that these are actually peaks rising and decreasing with a certain rate (which depends on the wear of the component divided by the time to substitute the component and on the delay due to a restart of production). It is relevant to notice it, since SD is a continuous simulation method and does not have any discrete events. These peaks are four and not six since the spindle and guideways are changed simultaneously.

This reflection is valid for all the peaks in the plots (that actually look like lines). The reason of this appearance is the long simulation period (180 months, which is fifteen years) compared to the length of the delays, which last even a fraction of a month. However, it was suitable to simulate for this simulation period, since it is of interest the behavior of the system throughout the whole machine tool life. Anyway it would be possible to see the dynamics of the system during these peaks, by just selecting a shorter time interval to be shown in the plots, as it is done for Figure 5.4.
As for the efficiency (calculated as a ratio between uptime and total production time), it will be reduced when the order rate will be higher and it will be necessary to produce during the weekends. This, indeed, will lead to an increment of downtime for preventive maintenance. The plot can be seen in the appendix.

- Machining system parameters
  Being the takt constant, the machining system parameters remain the same for both roughing and finishing, despite the demand is changing over time. The plots for the Feed Rate (Roughing) for both machining center and SPM, those for RPM and for the feed per tooth are shown in the appendix. Since the feed rate and the feed per tooth constant and the tool diameters are not varying, also the cutting speed will be constant and even the tool wear. The feed per tooth is also constant, although quite high – especially in the finishing operation – due to the low number of inserts.

If the demand increases or decreases, the system behaves accordingly, in a specular way. Therefore, in scenario 2, the situation is symmetric to scenario 1.
5.2.2.2 Actual situation – Base scenario 3

Having three machining center instead of two has some advantages. First of all it will be possible to answer the demand even when it gets the maximum value in the model (Figure 5.5).

![Figure 5.5: Order rate (blue), Throughput rate for SPM (red) and for MC (purple) with 3 MCs](image)

However, the costs are higher than with two machine tools, due to a higher capital cost and maintenance cost, since – passing from two to three machines – maintenance activities will be increased (see results in the appendix).

- Machining system parameters
  It is very relevant to notice that the cycle time will be shortened and it will then be possible to have a lower feed rate, as shown in Figure 5.6. The blue line shows the feed rate with two machines, while the red one shows the feed rate with three machines.
This will even lower down the RPM in the roughing operation, thus reducing tool wear and subsequently the tool cost (see plots in the appendix). The RPM in the finishing operation is kept constant, since the reduction of feed per tooth and hence of the cutting force is prioritized\textsuperscript{25}.

\textbf{5.2.2.3 Actual situation – Base scenarios 4-5}

From Figure 5.7 and 5.8 it can be noticed that a reduction of the time dedicated to preventive maintenance activities (excluding overhaul) will increase the number of drops in production and the peaks in the cost per part, due to more frequent substitutions of machine components. In the appendix, the results for scenario 4 are displayed as well. It can be seen that this machine tool is less robust to a reduction of preventive maintenance, the drops and peaks are, indeed, more frequent in the SPM case, while they did not appear with full time dedicated to preventive maintenance.

\textsuperscript{25} Cutting force is directly proportional to the maximum chip thickness that increases with the feed per tooth.
Looking better at the costs, it is possible to notice that, despite the peaks get more and more frequent while the time for preventive maintenance is decreased, the cost level is less when the time for preventive maintenance is reduced.

This happens because the increments in cost are mainly due to the cost for spare parts and for preventive maintenance that are both lasting for a very short period. On the other hand, the cost for preventive maintenance will be reduced. Moreover, the cost of overtime decreases as well: indeed, the reinforcing loop shown in Figure 4.5 shows that a reduction in time for preventive maintenance will lead to a decrease in total production time and
then of overtime costs. The same loop will make the capacity GAP decrease and therefore the maximum throughput will be higher. There will be no change in machining system parameters and in tool wear since the takt time and cycle time are the same.

5.2.3 Results from policy analysis

The results of the simulation with the three policies will be here displayed and discussed. The cases of the first two policies with the scenario of three machining centers are shown in the appendix. This is has not been done at all in the third scenario, since the latter is applicable for lower order rates that do not need a third machine.

5.2.3.1 Results for Policy 1

Figure 5.10 shows that with the policy, the SPM manages to fulfill the demand.

![Figure 5.10](image)

Figure 5.9: Order rate (blue), Throughput rate for SPM (red) and for MC (purple) with Policy 1

On the other hand, the MC is still not able to produce that maximum amount of products per month. This is due to the fact that, even though the takt will be shortened, the current feed rate that is used is already the maximum admissible in the model and therefore the process cannot be faster.

In Figure 5.10, the cost per part using the MC is still visibly higher than that implied from the SPM.
Moreover, with the activated policy, when the reduction of takt time is activated, although the tool cost per part will be higher because of an increment of feed rate and therefore cutting speed, the total cost per part will be lower (Figure 5.11).

This reduction of cost per part is due to the higher throughput and lower overtime costs than in the case without the policy. The cost per part for the machining center does not change (the plot can be found in the appendix).

- **Machining system parameters**
  During the third step of the order rate, since the takt time is decreased, the feed rate will be incrementated (Figure 5.12), as the other cutting parameters.
Figure 5.12: Feed rate for roughing operation SPM without (blue) and with (red) Policy 1

The results for the other machining system parameters and those for the machining center can be found in the appendix.

5.2.3.2 Results for Policy 2

With this policy, even if it is needed, the total production time will not be higher than the threshold (Figure 5.13).

Figure 5.13: Total production time SPM (blue), MC (red) and time threshold (purple) with Policy 2

In none of the cases, the order rate will be fulfilled and also here, the maximum capacity for the SPM is higher than for the MC. Also in this case the cost per part for the MC is higher than that for the SPM (see appendix).
The cost per part for the machining center does not change when the takt is changed in this policy (see in the appendix).

In the SPM case, instead, the cost per part will be lowered because if the takt is changed, the throughput will be higher. However, the difference is very low because, in contrast with the previous case, the overtime cost will be zero when the policy is active and in the scenario of benchmarking.

- Machining system parameters (see appendix)
5.2.3.3 Results for Policy 3

This policy is tested with a lower demand than the other policies (see the appendix). With this policy, the takt is varied and the demand can be fulfilled (Figure 5.16 a.).

Also with this policy, the cost per part for the SPM is lower than that for the MC (Figure 5.16 b.). In this policy, there will be a difference in the parameters in the two cases of the actual situation and the proposed policy. Figure 5.17 shows that there is actually an improvement in the cost per part for the MC if only the takt is adjusted.

This reduction of cost per part is due to a lower tool cost: indeed, if the takt time gets higher, then, to adjust the cycle time, the cutting parameters for the roughing operation (feed and speed) will be lower and as a consequence the tool wear and the tool cost. However, this is not valid for the SPM (see
appendix). In fact, in this case, the tools used for roughing are also used for finishing. Therefore their life is dimensioned to the parameters of finishing that do not change for quality reasons, as explained in chapter 4.

- Machining system parameters
In both cases (SPM and MC) the feed rate of the roughing operation is adjusted to slow down the process (Figure 5.18). The one for SPM is shown in the appendix together with the other plots.

![Figure 5.18: Feed Rate for roughing operation in MC without (blue) and with (red) Policy 3](image)

5.3 Discussion and recommendations

The results described in this chapter show that both productivity and cost improvements can be achieved by changing machining strategies. A variation of demand is one of the main causes that may vary performance targets and changing machining strategies can then be a good way to fulfill the new requirements that can arise. However, it is important to understand if the changes in demand will only last for very short periods or not. Indeed, the change of takt time will imply new targets for the workforce, which will need some time to be effective. On the other hand, if these changes are forecasted to be short, probably taking the advantage of producing during weekends would be more sustainable; of course this should not last for long time. Another very relevant point related to the modification of the takt time is the fact that this model is limited to the study of one machine tool that works in the broader context of a whole line. Therefore, it is necessary
to limit the takt reduction to the possible minimum takt for the bottleneck station. This is a limit of this model.

Considering the three analyzed policies, the first and the third allow to fulfill productivity requirements at lower costs. Although even the second policy would cause a decrease in costs, it is not suitable from productivity requirements, if the demand increases over a certain limit (confidential values for the company): however, the numerical values are not exact and even with this demand the required takt would be very low. Therefore, policy 2 is not suggestible.

As for the choice between a special purpose machine and a machining center for this kind of operation, from both cost and productivity points of view, the SPM is more convenient. However, it has to be kept in mind the importance of preventive maintenance for this machine tool concept, especially with the components that it currently has. Even from a quality point of view, the higher robustness of this concept is an advantage, though dynamic stability has to be monitored to prevent failures and accuracy problems. Nevertheless, the model does not take into account the effect of the stops for breakdown or preventive maintenance on the whole line, which would underline a big drawback for the SPM. Indeed, even if the machine tool was put in a plant with a cellular layout and not in a transfer line, since only one SPM is required, all the downtime of this machine will directly affect the productivity of the entire production flow. Another advantage of the machining center is that it brings the possibility to invest in steps: should the demand increase, another machine can be bought with much lower investments costs than for a SPM. A further point of reflection is the opportunity of having a SPM with two stations, one for roughing and one for finishing. This solution could also be tested by varying input parameters and with some slight changes in the model structure. Another important point in the investment on a new machine tool is the collaboration and communication between production and maintenance: it is not only important the nature of the machine tool – if it is a SPM or a machining center – but also their components. As the models show, different components will need different maintenance activities that will
highly affect production and in turn, different operational policies will then bring more or less need for corrective maintenance.

The big advantage that can be taken out from this framework is to show, not only with common sense, but even with simulated data, how different parameters from different areas are related to each other and how will affect long-term results.
6. Conclusions and future work

This work shows a framework for the evaluation of machining strategies applied to a machine tool concept evaluation in the production of cylinder-blocks. This last chapter will present conclusions and comment on future work that should be done in this topic.

6.1 Conclusions

In order to summarize and explain the results, it is worth to go through the research questions formulated in Chapter 1.

1. *Is it possible to build a model for the evaluation of machining strategies that takes into account how the machining system and its performances are related to each other? And, if so, is SD a suitable methodology to do it?*

It is actually possible to model the machining system, its performance indicators and their inter-relationships and to simulate the system behavior in order to evaluate different machining strategies. The presented models show that SD is a suitable tool to model complex systems, in which feedbacks are dominant to create the behavior of the system itself. The system comprising the machining system and its derived performance corresponds to this description and can be modeled and simulated through SD. A big advantage that this choice entails is the possible re-utilization of
different “blocks” of the model, when another kind of setup or machining strategy has to be evaluated. It is also interesting to notice that the methodology allows to see changes in performance behavior when input parameters are changed. This is possible because a SD model detects the feedbacks that are always relevant in complex system and contains all the relationships between variables that can be of different nature. This last point is achievable since a SD models allows the user to build qualitative relationships that do not need to be mathematically proven. Moreover, machining strategies can be tested throughout the whole machine tool lifespan, which is very important, since synthetic statistical data will not show the system behavior that can consistently change through time.

2. Which are the main drivers to improve machining system performance?

The simulation results show that the system is sensitive to the variation of cutting parameters. In particular, changing feed rate affects productivity performance and by varying the cutting speed the cost per part is influenced. The policy of adjusting capacity through a change in total available time or takt time has also an impact on machining system performance. Moreover, a variation of maintenance policies will also change machining system performances. Finally, the choice of a machine tool concept and its components affect the behavior of the system and its performance.

3. How and how much will the drivers affect machining system performance?

The way in which the aforementioned drivers affect the machining system performance depend, of course, on the targets. The targets, if quality is only considered as a constraint – as it is in this case – mainly depend on the demand to fulfill. If the order rate increases, then, productivity requirements should be met: in this case, it is a suitable choice to speed the process up (this, of course, if quality requirements are met) by incrementing feed rate and cutting speed or feed per tooth. If the cutting speed is increased, the tool cost will grow, but this would be compensated by a lower cost per part because of a higher throughput. On the other hand, if the
demand decreases, in order to limit the increase of cost per part, slowing down the process by setting a higher takt is a good solution. Indeed, Anyway the models shows both productivity and cost improvements when both total production time and takt time (and therefore cutting parameters) are adjusted to meet higher demand and when only takt time is prolonged to manage a drop in demand. It is worth to underline that improvements in costs shown in the model results foresee decreases in costs of some cents of Swedish Krona per part: this could be a big save of money, if applied to the production of one month or year. However, as it was already mentioned, the reliability of numerical results is limited by the lack of some information, especially regarding maintenance costs, the presence of numerous assumptions and the fact that SD methodology focuses more on trends and dynamical behavior than on numerical synthetic values. For this reason, it is always better to couple this instrument with other kind of static evaluation methods.

4. Which machine tool concept is the most suitable for the face milling of the two cylinder-block sides?

The simulation results show that the SPM is more suitable, especially in the case of increasing demand, because of its higher capacity. However, as it has been already mentioned in the discussion, the components of each machine tool have to be considered, rather than limiting the analysis to the machine tool concept. In both cases of using a SPM and MC, preventive maintenance activities have to be executed and an analysis of the effect of the choice on the whole line production should be coupled to this model.

6.2 Future work

Being this work a part of a much bigger project, there is still a great amount of future work to improve this unified concept.

First of all, the part accuracy should be incorporated in the model and has to be seen as a performance factor to improve, more than only a constraint. However, in order to do it, since quality must not be compromised, it has to be kept in mind that this model will always have qualitative components
and users should not rely on its numerical values, while the system behavior has to be considered instead. As a consequence, it is suggestible to run tests on the part, in order to set robust and reliable limits to cutting parameters. In the analysis of the accuracy, parameters regarding the machine tool elastic structure should be included. A control loop for the force, regulating its maximum limit through the maximum available power for the machine and the sustainable level of forces for the structure would also help to set reasonable limits to machining system parameters. Furthermore, seeing the effect of changing machine tool components to the system structure and behavior would be of interest for the analysis of different kinds of machine tools. Moreover, similar models for other machining operations could be built.

It would also be interesting to simulate the model for other kinds of variations, apart from the order rate. For example, it is of relevance to evaluate machining strategies in case of change in product specification or component material. Testing the model in reality would be a step forward to understand the limitations and advantages that can be taken out from this simulation method.

Finally, it would be very important to test the possibility to re-use the different parts or “sectors” of the models for similar applications. This would be a crucial step to prove the utility of this unified framework that could be of huge support to have also a holistic, although partially qualitative, perspective in the evaluation of machining strategies, when new machining setups have to be implemented and when new sources of variation in demand or in product specification and materials arise.
References


[19] ISEE help STELLA/iThink


[27] European Standard EN 13306

Appendix

Appendix Chapter 4

Appendix Figure 1: Complete CLD
Appendix Figure 2: Machining system parameters used in the models

Appendix Figure 3: Other used parameters
<table>
<thead>
<tr>
<th>Component</th>
<th>Old line</th>
<th>New line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With preventive maintenance</td>
<td>No preventive maintenance</td>
</tr>
<tr>
<td>Ball screws</td>
<td>15 yrs</td>
<td>7 yrs (not sure)</td>
</tr>
<tr>
<td>Guideways</td>
<td>15 yrs</td>
<td>6-8 months (40hrs to change box g.)</td>
</tr>
<tr>
<td>Spindle bearings</td>
<td>15 yrs</td>
<td>12 years</td>
</tr>
</tbody>
</table>

**Appendix Table 1: Component lifespan**

**Appendix Figure 4: Machining system parameters sub model**
Appendix Figure 5: Operational and maintenance sub-model
Appendix Chapter 5 (all the plots have non-displayed numbers on the y-axis for confidential reasons)

Appendix Figure 6: Order rate in testing 1

Appendix Figure 7: Order rate in testing 2
Appendix Figure 8: Order rate in testing 3

Appendix Figure 9: Order rate in scenario 2
Results from testing with average demand:

Appendix Figure 10: Total production time SPM(blue), MC(red) and time threshold (purple)

Appendix Figure 11: Order rate (blue), throughput rate SPM (red) and MC (purple)

Appendix Figure 12: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 13: Tool cost per part SPM (blue) and MC (red)
Appendix Figure 14: Cycle time SPM (blue) and MC (red), takt (purple)

Appendix Figure 15: Feed per tooth SPM (left) and MC (right)
Results from testing with high demand:

Appendix Figure 16: Order rate (blue), throughput rate SPM (red) and MC (purple)

Appendix Figure 17: Total production time SPM(blue), MC(red) and time threshold (purple)

Appendix Figure 18: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 19: Cycle time SPM (blue) and MC (red), takt (purple)
Appendix Figure 20: Tool cost per part SPM (blue) and MC (red)
Results from testing with low demand:

Appendix Figure 21: Order rate (blue), throughput rate SPM (red) and MC (purple)

Appendix Figure 22: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 23: Cycle time SPM (blue) and MC (red), takt (purple)

Appendix Figure 24: Total production time SPM (blue), MC (red) and time threshold (purple)
Appendix Figure 25: Efficiency SPM (purple) and MC (green)

Appendix Figure 26: Tool cost per part SPM (blue) and MC (red)

Appendix Figure 27: Feed per tooth SPM (left) and MC (right)
Results from actual situation Scenario 1:

Appendix Figure 28: Total production time SPM (blue), MC (red) and time threshold (purple)

Appendix Figure 29: Overtime cost per part SPM (blue) and MC (red)

Appendix Figure 30: Maintenance cost per part SPM (blue) and MC (red)

Appendix Figure 31: Tool cost per part SPM (blue) and MC (red)
Appendix Figure 32: Efficiency SPM (purple) and MC (green)

Appendix Figure 33: ROM MC Roughing

Appendix Figure 34: Feed per tooth SPM (left) and MC (right)
Results from actual situation Scenario 3:

Appendix Figure 37: Total production time SPM (blue), MC (red) and time threshold (purple)

Appendix Figure 38: Overtime cost per part SPM (blue) and MC (red)

Appendix Figure 39: Maintenance cost per part SPM (blue) and MC (red)

Appendix Figure 40: Tool cost per part SPM (blue) and MC (red)
Appendix Figure 41: Efficiency SPM (purple) and MC (green)

Appendix Figure 42: Feed per tooth MC (left) and SPM (right)
Results from actual situation Scenario 4:

Appendix Figure 43: Order rate (blue), throughput rate SPM (red) and MC (purple)

Appendix Figure 44: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 45: Maintenance cost per part SPM (blue) and MC (red)

Appendix Figure 46: Efficiency SPM (purple) and MC (green)
Appendix Figure 47: Component wear SPM

Appendix Figure 48: Component wear MC

Appendix Figure 49: Overtime cost per part SPM (blue) and MC (red)

Appendix Figure 50: Tool cost per part SPM (blue) and MC (red)
Appendix Figure 51: Feed per tooth SPM (left) and MC (right)
Results from actual situation Scenario 5:

Appendix Figure 52: Total production time SPM(blue), MC(red) and time threshold (purple)

Appendix Figure 53: Tool cost per part SPM (blue) and MC (red)

Appendix Figure 54: Overtime cost per part SPM (blue) and MC (red)

Appendix Figure 55: Feed per tooth SPM (left) and MC (right)
In all the results with policies, when it is not specified, the results are after the policy is activated.
Results from Policy 1:

Appendix Figure 58: Total production time SPM(purple, 1), MC(red) and time threshold (purple, 3)

Appendix Figure 59: Efficiency SPM (blue) and MC (red)

Appendix Figure 60: Takt (blue) and cycle time (red) SPM

Appendix Figure 61: Throughput rate MC before (blue) and after the policy (red)
Appendix Figure 62: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 63: Takt (blue) and cycle time (red) MC

Appendix Figure 64: Tool cost per part SPM (blue) and MC (red)

Appendix Figure 65: Feed per tooth MC (left) and SPM (right)
Appendix Figure 66: RPM MC Roughing before (blue) and after (red) the policy

Appendix Figure 67: Feed rate MC Roughing before (blue) and after (red) the policy

Appendix Figure 68: RPM SPM Roughing before (blue) and after (red) the policy
Results from Policy 2:

Appendix Figure 69: Perceived cost per part SPM (blue) and MC (red)

Appendix Figure 70: Perceived cost per part SPM MC before (blue) and after (red) the policy

Appendix Figure 71: Takt (blue) and cycle time (red) SPM

Appendix Figure 72: Takt (blue) and cycle time (red) MC
Appendix Figure 73: RPM SPM before the policy (blue) and after (red)

Appendix Figure 74: Feed rate SPM before the policy (blue) and after (red)

Appendix Figure 75: Tool cost per part before the policy (blue) and after (red)

Appendix Figure 76: Efficiency SPM (blue) and MC (red)
Appendix Figure 77: Feed per tooth MC (left) and SPM (right)
Results from Policy 3:

Appendix Figure 78: Feed rate SPM Roughing before the policy (blue) and after (red)

Appendix Figure 79: RPM SPM Roughing before the policy (blue) and after (red)

Appendix Figure 80: Perceived cost per part SPM before the policy (blue) and after the policy (red)

Appendix Figure 81: RPM MC before the policy (blue) and after (red)
Appendix Figure 82: Takt (blue) and cycle time MC (red)

Appendix Figure 83: Takt (blue) and cycle time SPM (red)

Appendix Figure 84: Feed per tooth MC (left) and SPM (right)

Appendix Figure 85: Efficiency SPM (blue) and MC (red)