Flexibility in Aerospace and Automotive Component Manufacturing Systems: Practice, Strategy and Optimization

by

Dominic Hauser

Master Thesis written at the
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Abstract

Traditionally, parts fabrication in the aerospace and automotive industries has been associated with a number of manufacturing processes. The traditional metrics for assessing competing processes are quality, cost and production rate. Forming technology and machining, e.g., can be compared based on process capability, fixed cost for equipment and tooling as well as per unit cost as a function of production volume. Increasingly, however, market driven uncertainties are starting to dominate fabrication process design and selection. Two types of uncertainties are of particular interest: demand fluctuations and part specification changes. This thesis surveys flexibility strategies and practices that allow enterprises to quickly and cost effectively respond to changes in both demand and specification. The literature on parts fabrication flexibility is thoroughly reviewed and the discussion is augmented with data and interviews obtained from a number of companies. A simple 'lever' example is worked out in order to illustrate the fundamental metrics and mathematics involved in assessing parts manufacturing flexibility. It is shown that production volume remains an important ingredient of any flexibility strategy, leading to different regimes for the aerospace and automotive industries. The thesis lays out a set of generic flexibility strategies and sets the groundwork for a more comprehensive flexibility optimization framework.

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Nomenclature

Abbreviations

AMT	Advanced Manufacturing Technology
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CTO	Chief Technology Officer
FMS	Flexible Manufacturing System
GBM	Geometric Brownian Motion
IRR	Internal Rate of Return
JIT	Just In Time supply concept
M	Mobility
Max	Maximum value
Min	Minimum value
MUR	Machine Utilization Ratio
NPV	Net Present Value
R-H	Range Heterogeneity
R-N	Range Number
SMED	Single Minute Exchange of Dies
STD	Standard deviation
U	Uniformity

Symbols

C	Cost, Costs, [$]

CAP_d	Capacity per day, [parts]
C_M	Machine cost, [$]
C_{M_H}	Machine costs per hour, [$]
C_{M_P}	Machine costs per part, [$]
C_{Man}	Manufacturing costs, [$]
C_{Man_P}	Manufacturing costs per part, [$]
C_{Mat_P}	Material costs per part, [$]
C_{Mat_U}	Material unit price, [$]
$C_{Overdue}$	Cost for overdue parts, [$]
C_{PQ_P}	(Production) Quantity dependent costs per part, [$]
C_{PT_P}	(Production) Time dependent costs per part, [$]
C_S	Switching costs, [$]
C_{S_P}	Switching costs per part, [$]
C_{Stock}	Costs for stock keeping, [$]
C_{Tc}	Costs of common tool, [$]
C_{Tc_P}	Costs of common tool per part, [$]
C_{Td}	Costs of dedicated tool, [$]
C_{Td_P}	Costs of dedicated tool per part, [$]
C_{Tot}	Total costs of a single product, [$]
C_{v_H}	Variable costs per hour, [$]
C_{v_P}	Variable costs per part, [$]
D	Demand, [parts]
E	Earnings, [$]
E_{Tot}	Total Earnings, [$]
L	Length, [length unit]
L_A	Length of lever A, [length unit]
L_B	Length of lever B, [length unit]
L_C	Length of lever C, [length unit]
L_D	Length of lever D, [length unit]
L_P	Length of a part, [length unit]

L_α	Length of lever α, [length unit]
L_β	Length of lever β, [length unit]
L_γ	Length of lever γ, [length unit]
n	Number
n_D	Number of work days per year
n_H	Number of work hours per shift
$n_{Overdue}$	Number of overdue parts
n_S	Number of shifts per day
n_{Stock}	Number of parts in stock
P_A	Actual production, [parts]
P_T	Target production, [parts]
R	Revenue, [$]
R_P	Revenue per part, [$]
r_{Mat}	Material utilization ratio, [%]
$r_{Machine}$	Machine utilization ratio, [%]
r_{Output}	Output rate, [parts/minute]
$r_{Overdue}$	Rate of overdue part costs, [%]
$r_{Overhead}$	Charge for overhead costs, [%]
r_{Scrap}	Scrap rate, [%]
r_{Stock}	Rate of annual stock costs, [%]
S	Sales, [parts]
S_A	Sales volume of part A, [parts]
S_B	Sales volume of part B, [parts]
S_C	Sales volume of part C, [parts]
T	Time
t	Time index, current period
T_{LM}	Machine lifetime, [years]
T_{LT}	Tool lifetime, [parts]
T_{P_P}	Production time per part, [hours]
T_S	Switching time, [hours]

V_{Fin}	Final value of tools, [$]
V_{Tc}	Current value of common tool, [$]
V_{Td}	Current value of dedicated tool, [$]
α	Constant in quadratic cost function
β	Constant in quadratic cost function
Γ	Random number in GBM
δ	Constant in quadratic cost function
μ	Expected return per time unit in GBM
σ	Standard deviation in GBM

Chapter 1

Introduction

1.1 Problem Definition

1.1.1 Background

Traditional component manufacturing systems in the aerospace and automotive industries have been geared and optimized for mass production of a small variety of high (demand) volume parts. Market demand fluctuations and the trend for providing a larger variety of parts have exposed the need for embedding more flexibility in manufacturing systems and processes. But, what is flexibility? Schulz and Fricke [SF99] and [FSWN00] use a matrix as shown in Figure 1-1 to distinguish the different designs of changeability. However, they talk mainly about the parts and product systems themselves rather than processes, their concept can be used to delimit process flexibility from process changeability. The authors define *flexibility* as the systems ability to *change easily*. Therefore, as with *agility* they understand a systems ability to *change rapidly*. Flexibility and agility describe the situation within the system itself whereby flexibility is a prerequisite to achieve agility, i.e., agility is an evolutionary level of flexibility. For characterizing the interactions with the systems environment Schulz and Fricke use robustness and adaptability. While *robustness* defines the systems ability to be insensitive towards changes within its environment, *adaptability* specifies a systems ability to adapt itself toward its environment without external ac-

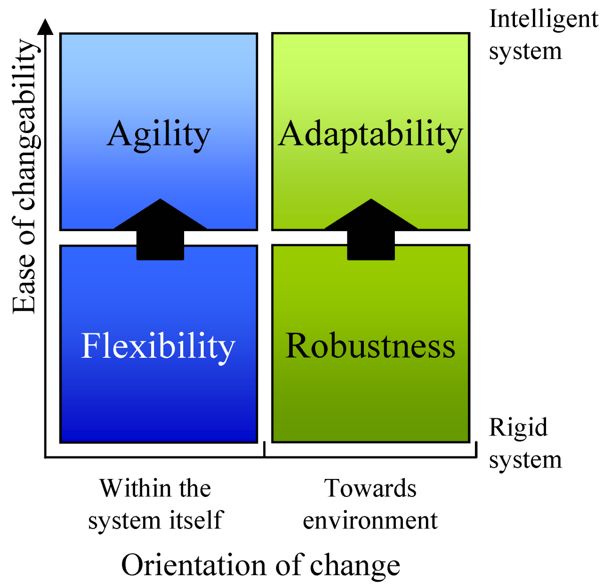

Figure 1-1: Flexibility versus agility, robustness, and adaptability

tuation. This implies embedded intelligence (see Figure 1-1). Analogous to flexibility and agility, robustness is a prerequisite to achieve adaptability, i.e., adaptability is the evolutionary level of robustness.

For systems with mechanical elements, flexibility can be embedded at the parts manufacture level, at the assembly level or both. The focus of this thesis is on flexibility in parts manufacturing and on metal components in particular. This flexibility must primarily accommodate changes in the following attributes:

a) **Capacity**. The capacity of a production facility can be measured as the number of units that can be produced per time unit. Sizing of capacity is primarily driven by the expected demand for particular types of components. Craftsmanship-type processes are flexible, but only competitive for small volumes. Highly automated processes have high capacity, but require large investments in tooling and machinery and are only competitive for large volumes. In Figure 1-2 cost curves depending on the number of produced parts of two manufacturing process technologies (e.g. stamping and machining) are compared. Stamping has higher fix costs for tooling than machining, but therefore, has lower variable production costs, especially due to the higher output rate (e.g.,

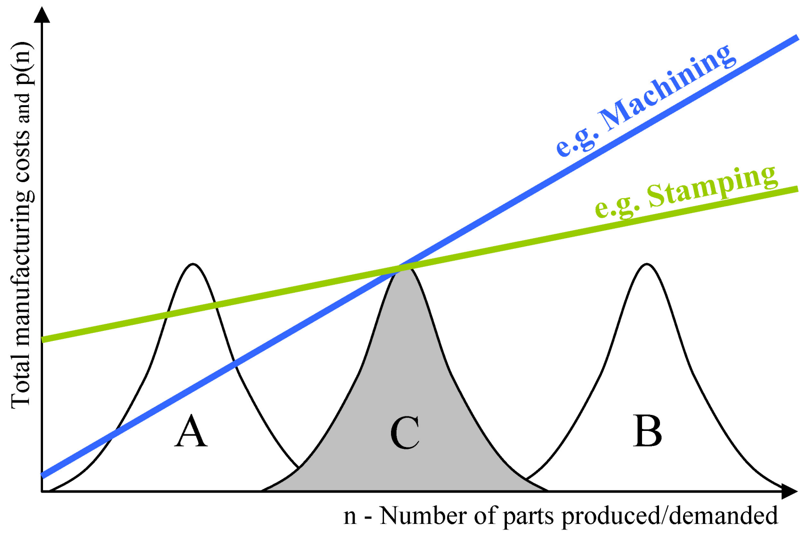

Figure 1-2: Manufacturing cost curve and likelihood of number of parts

see [Rei00] and [Rei01]). So, there exists a crossover point. The production quantity at the crossover point is called *break-even point*. Given the fixed and variable costs of two processes, the break-even point N can be calculated as (see [Sei98])

$$N = \frac{C_{fix_{Process1}} - C_{fix_{Process2}}}{C_{var_{Process2}} - C_{var_{Process1}}} \tag{1.1}$$

If the expected distribution of the demand is like in case A (see Figure 1-2) it is clear that a firm will use the 'machining' process. On the other side, if the demand is distributed as shown in case B, there is no question that 'stamping' will be more profitably. The crucial question now is, which process technology should be chosen if the demand is distributed around N (case C). One possible solution to this problem is to search for a new process whose total costs at the production quantity N are lower than those of the other processes.

b) **Part Specifications**. The primary specifications of structural components consist of geometrical dimensions and tolerances, e.g., a bicycle company will use different parts to fulfill a specific function in their 'racing' and 'family' bikes. Some manufacturing processes are inherently more flexible than others in terms of accommodating such specification changes. In Figure 1-3 *high speed machin-*

ing, *forming technology*, *punching*, *casting*, *prototyping*[1], and *laser beam cutting*[2] are compared qualitatively to each other according their process switching time, their productivity and their ratio of variable to fix costs[3]. The processes have been arranged by determining their position in the classification precision of low - mid - high. As one knows by experience, the more to the left a process

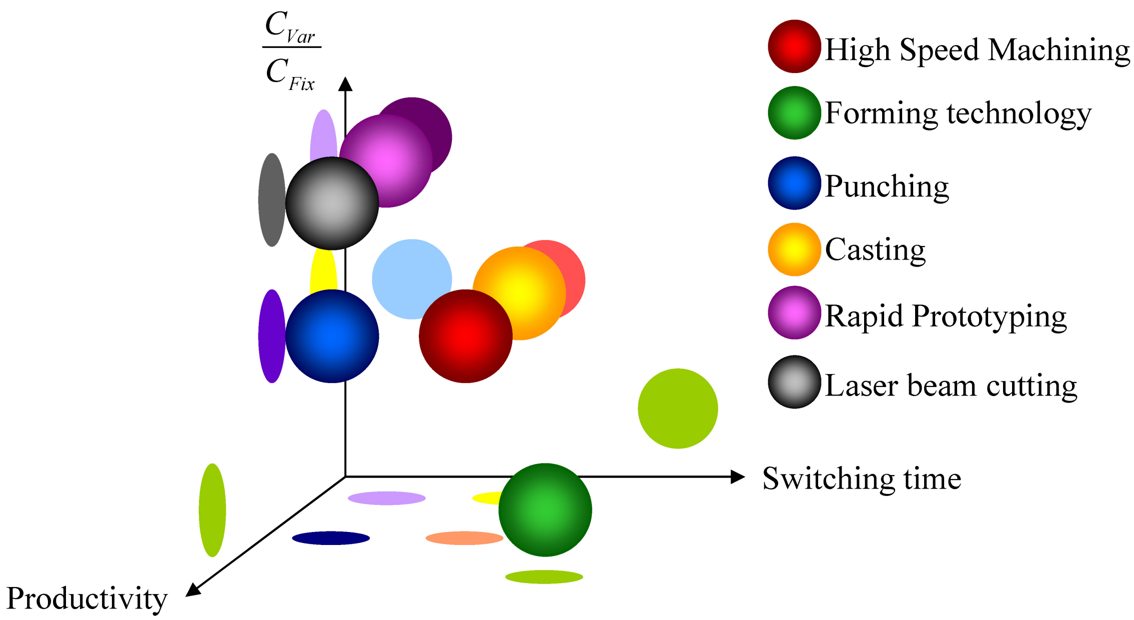

Figure 1-3: Some manufacturing processes

is located in Figure 1-3, the easier switching manufacturing from one part to another can be made. The more upward a process is placed in this chart the easier new parts can be added to the current product range. Lower processes require more fixed investments, e.g. for tools. The third dimension, productivity, gives a statement on how many units per time can be manufactured with a given process technology. The further in the front a process is located the higher is its output rate. As can be seen, the aim is to reach a process in the upper left front corner. In case of high speed machining the Flexible Manufacturing Systems (FMS) have already brought a big advantage in this direction.

[1] e.g. Stereolithography Apparatus (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Z Corp Three-Dimensional Printing (3DP), or Objet Polyjet (OBJ)

[2] Water jet cutting would be in the same category as laser beam cutting (see Section 3.2.2)

[3] Here, only fixed costs for tools are considered

See e.g. Buffa [Buf94] who says that: ‘an economical run can be as low as one unit for operations where NC and FMS are applicable’, and Jaikumar [Jai86]: ‘U.S. companies used the FMSs the wrong way – for high-volume production of a few parts rather than for high-variety production of many parts at low cost per unit’.

1.1.2 Research Questions

Original Equipment Manufacturers (OEMs) are currently struggling with a number of questions regarding flexibility in their component manufacturing systems. The key questions are:

- What is the current state-of-the-art in flexible component manufacturing systems? Can new processes (e.g. hydro-forming) increase flexibility?

- What are best practices of competitors in the same industry and in related industries regarding flexible component manufacturing systems?

- What are different strategies for achieving flexibility in the capacity of a manufacturing system (separate, parallel lines that can be activated as needed, adding shifts, outsourcing during demand peaks, etc.)?

- How do the fixed, variable and total per-part costs change as different manufacturing processes are scaled up in terms of the number of units produced? Where are the crossover points between metal forming and high speed machining processes as a function of the number of units?

- Which processes are more flexible than others in terms of part geometries and specifications (surface roughness, thickness distributions, pre-stress levels)? How can this flexibility be quantified?

- Where and how can modern concepts such as virtual production planning and simulation or modular tooling be leveraged to increase flexibility?

- Given stochastic estimates of future demand in terms of part geometries and number of units to be produced, can we conceive of a scheme to optimize the strategy for and architecture of flexible manufacturing systems?
- What are the quantifiable benefits and penalties of embedded flexibility?

1.1.3 Research Scope

Since this research topic has a very large scope it must be limited in order to ensure the success of the research. The scope is limited in the following ways:

- **Processes:** Focus only on metal forming processes versus high speed machining. An example of a past process decision is the manufacturing of avionics equipment shelves on the F/A-18 E/F aircraft via high-speed machining rather than Superplastic Forming (SPF).
- **Applications:** Focus on the automotive (high volume) and aerospace (low volume) industries only. A sample of four to six representative companies from these two industries should be studied as part of the thesis.
- **Tooling:** Focus on aspects of manufacturing machines, tooling and system layout optimization, since this is where most of the investment cost is determined.

1.1.4 Research Objective

Establish the state of the art in flexible component manufacturing systems with emphasis on metal forming processes and develop a supporting taxonomy and optimization framework. In the course of doing the research, answer as many of the research questions posed in Section 1.1.2 as possible.

1.2 Flexibility in Manufacturing

Before starting with the core of the research, a short 'tour d'horizon' is made about the emergence of flexibility in manufacturing. In Figure 1-4 the evolution of manufacturing 'types' is illustrated. Beginning in the middle ages, the chart shows roughly

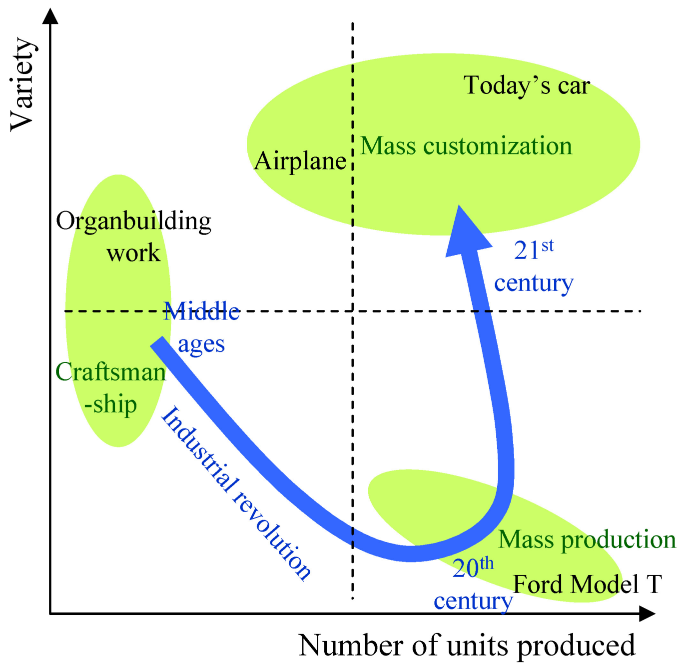

Figure 1-4: Manufacturing types over the centuries

how the variety of the products and the number of produced parts changed over time. Before the industrial revolution hardly one part was exactly the same as an other. Then at the beginning of the last century mass production emerged at the expenses of variety. Today's challenge is so called mass customization, offering a wide variety of products (customized) that are produced in the same manner as mass products (benefiting from economies of scale). Since the focus of this thesis is on the upper right quadrant of Figure 1-4 where flexibility in the manufacturing process is needed, some more information about the genesis of flexibility in manufacturing is provided here.

According to Suarez et al. [SCF95], three main 'strategic imperatives' have emerged during the last century. With the advent of scientific management, early in the 1900s, *efficiency* became the key strategic imperative for many companies. Given the rapid, remarkable success of Ford Motor Co. with its focus on efficiency postulated by the scientific management school, the diffusion of this imperative was fast and widespread; soon after Ford's successful growth and transformation, many companies in many sectors began to focus on improving efficiency in their operations.

Around the middle of the last century, particularly after W. Edwards Deming and Joseph Juran visited Japan, *quality* emerged as a new strategic imperative in the marketplace. The market not only valued efficiency and low prices, but started to care more directly about the quality of products and services. As it is known from the history of the quality movement, it took managers longer to understand the importance of quality than the importance of efficiency (the quality movement can be traced to the early 1900s in the United States). Deming's and Juran's visits to Japan, and the willingness of Japanese managers to hear and apply their suggestions, started a slow process by which quality gradually became the second strategic imperative of the 1900s; only at the end of the 20^{th} century the concept has gained widespread attention.

The third strategic imperative, *flexibility*, emerged as a result of the instabilities of the 1970s and the increased global competition in most world markets starting in the 1980s. Increased competition means more volatile markets, shorter life cycles, and more sophisticated buyers, which have all contributed to the flexibility's emergence as a new strategic imperative.

1.3 Summary

To outline the problem area of this thesis first a broad definition of flexibility is given. *Flexibility as a systems ability to change easily* is set in contrast to agility, robustness, and adaptability. Then two important attributes for systems with mechanical elements, changes in capacity and changes in part specifications, are discussed in some detail. As an outcome of that debate several research questions are formulated. These then are narrowed down to focus on metal forming processes, on aerospace and automotive (low and high volume) industry, and on machine, tooling, and systems layout. Finally, a short review of the emergence of flexibility in manufacturing systems is given.

Chapter 2

Literature Survey and Interviews

In 1995, Upton [Upt95b] wrote: ‘Ten or 15 years ago, quality was much like flexibility is today: vague and difficult to improve yet critical to competitiveness (...) Flexibility is only beginning to be explored (...) It means different things to different people.’

The ambiguity of the term *flexibility* is still present. Trying to clarify this fuzziness in this chapter first, after a short outline of the wide field of manufacturing flexibility, different types of flexibilities are defined. The second step shows approaches how to measure flexibility. Before pointing out some strategies, different methods how to value flexibility are presented. The outcomes of several interviews are discussed at the end of this chapter.

2.1 Introduction

Probably one of the first authors who dealt with flexibility was Stigler [Sti39]. He refers to the attribute of cost curves that determines how responsive output decisions are to price fluctuations such as *flexibility* (Mills [Mil84]), see Appendix B for a discussion of that curve. Stigler’s notion of flexibility is one that varies inversely with the curvature of the total cost curve, or the slope of the marginal cost curve. Flexibility is least when marginal costs are steep and average costs rise precipitously around their minimum; flexibility increases as average costs are flatter and marginal costs less steep. Figure 2-1 (reproduced from Mills, corresponding to the relevant figure in Stigler) shows two average cost curves and their corresponding marginal cost curves[1]. The 'one' pair of curves shows greater flexibility than the 'two' one, i.e. manufacture process 'one' is more flexible than process 'two'. Notice that minimum

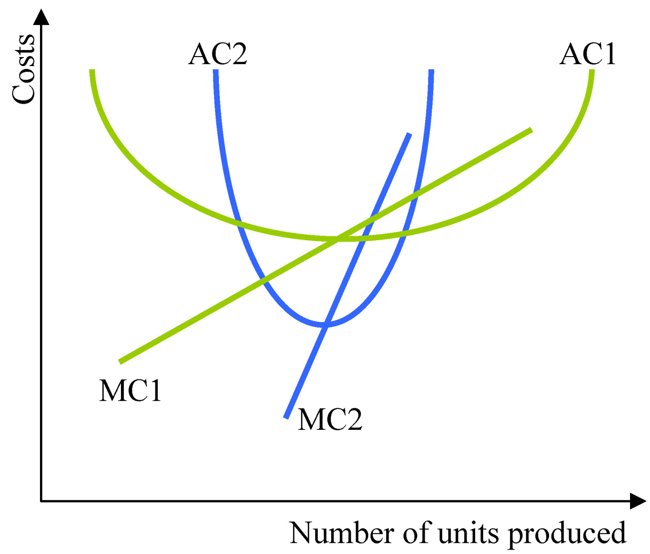

Figure 2-1: Flexibility and cost curves

average costs are shown to vary inversely with flexibility, i.e., attributes of internal organization to increase flexibility will also inflate costs per unit when the output is near capacity. (The fact that both average cost curves are minimized at the same output level is inessential and merely facilitates comparisons.) As Stigler put it: 'Flexibility will not be a 'free good': A plant certain to operate x units of output per week will surely have lower costs at that output than will a plant designed to be passably efficient from $\frac{x}{2}$ to $2x$ units per week.'

Today it seems obvious that there are different types of flexibilities and Stigler's model only describes one type of flexibility. It is known today as *volume* flexibility, and, of course, his definition using cost curves is exactly the other way around for *product* flexibility (see Section 2.2).

Flexibility is generally defined as 'the ability to change or react with little penalty in time, effort, cost, or performance' (e.g., Upton [Upt94]). And it has been widely recognized as a 'multi-dimensional concept within the manufacturing function' (e.g.,

[1]For mathematical explanation of the cost curves see Appendix B.

Sethi and Sethi [SS90]).

There is no doubt, that flexibility remains a key strategic objective to many manufacturing companies (Beach et al. [BMP+00]). They refer to Adam and Swamidass [AS89] who assert that 'the core content of a manufacturing strategy includes cost, quality, flexibility and technology' and Collins and Schemmer [CS93] who note that when asked to articulate the manufacturing task the usual priorities mentioned are: 'product quality, product cost, delivery dependability, and flexibility'.

Nonetheless, the acquisition of flexible technology, e.g. FMS or AMT, as a direct response to changing markets is not necessarily the panacea it is widely believed to be. Indeed, in some circumstances, the trade-offs that must be made between dedicated equipment and flexible technology may restrict competitiveness (Hill and Chambers [HC91]). This point is supported by Kulatilaka and Marks [KM88] who conclude, 'the strategic value of flexibility can, under some conditions, be negative', particularly, when uncertainty can be limited or constrained by contract. In short, 'more flexibility does not always mean a more economic solution' particularly when economies of scale are high (Gupta [Gup93]). Therefore 'without a clear strategic direction with regard to manufacturing, the new manufacturing technologies can become an expensive solution in search of a problem' (Correa [Cor94]). Jaikumar [Jai86] attributes in his comparative study of Japanese and US FMS the superior performance of Japanese systems not to flexible technology, but rather to their technological literacy. In the same article he emphasizes the integrative task of running AMT: 'In company after company in Japan, systems engineers with a thorough knowledge of several disciplines have proved the key to the success of flexible manufacturing systems.'

As Beach et al. [BMP+00] write, two of the most comprehensive and informative studies about manufacturing flexibility have been done by Sethi and Sethi [SS90] and by Gupta and Goyal [GG89]. The work of Gupta and Goyal is concerned with the classification of the literature based on the different ways in which flexibility has been defined. They adopt the eight types of flexibility defined by Browne et al. [BDR+84] and put them in a matrix as the headers of the columns. Each row then presented the terms for that type of flexibilities used by a particular author, so it can be used now as a ‘dictionary’, see Table 2.1. In the second study by Sethi and

Author(s)	Machine	Process	Product	Routing	Volume	Expansion	Process Sequence	Production
Mandelbaum [Man78]		Action						State
Buzacott [Buz82]	Machine	Job						
Son and Park [SP87]	Process		Equipment		Demand			Product
Zelenovic [Zel82]		Adaptation						Application
Gerwin [Ger82]		Design	Parts	Routing	Volume			Mix
Frazelle [Fra86]		Design	Parts	Routing	Volume			Mix
Carter [Car86]	Machine	Mix	Mix Change	Routing		Expansion		Production
Azzone and Bretele [AB87]		Process	Product	Routing				Production
Barad and Sipper [BS88]	Machine Setup	Process		Routing			Operations	
Chatterjee et al. [CCMM84]		Part Specific	Part Mix	Routing				
Gustavsson [Gus84]			Product		Demand	Machine		
Slack [Sla83]		Quality	New Product		Volume			Product Mix

Table 2.1: Classification of flexibility literature according to Browne et al., reproduced from Gupta and Goyal [GG89]

Sethi, Gupta and Goyal’s eight flexibility types are expanded to eleven. This work places manufacturing flexibility firmly in a wider context of the organization and the business environment and, therefore, the strategic flexibility arena, emphasizing the role these broader issues play in the pursuance of flexibility (Beach et al.). Gupta and Somers [GS92] honor the work of Sethi and Sethi as ‘one of the most thorough classification systems’.

Therefore, their work is likely to be the most cited article in literature about manufacturing flexibility. So, the definitions given by Sethi and Sethi will be used in this thesis.

2.2 Types of Flexibilities

2.2.1 Definitions by Sethi and Sethi

The eleven types of flexibility are: machine, material handling, operation, process, routing, product, volume, expansion, program, production, and market flexibility. The first three of the eleven are considered as basic system components, while the other eight apply to the manufacturing system as a whole. Sethi and Sethi also acknowledge that sophisticated computer and information technology and a flexible organizational structure underlie each of the flexibility types. Figure 2-2 (reproduced from Sethi and Sethi, [SS90, p. 297]) provides a convenient overview of the various flexibilities under consideration. It is explained later after giving the definitions,

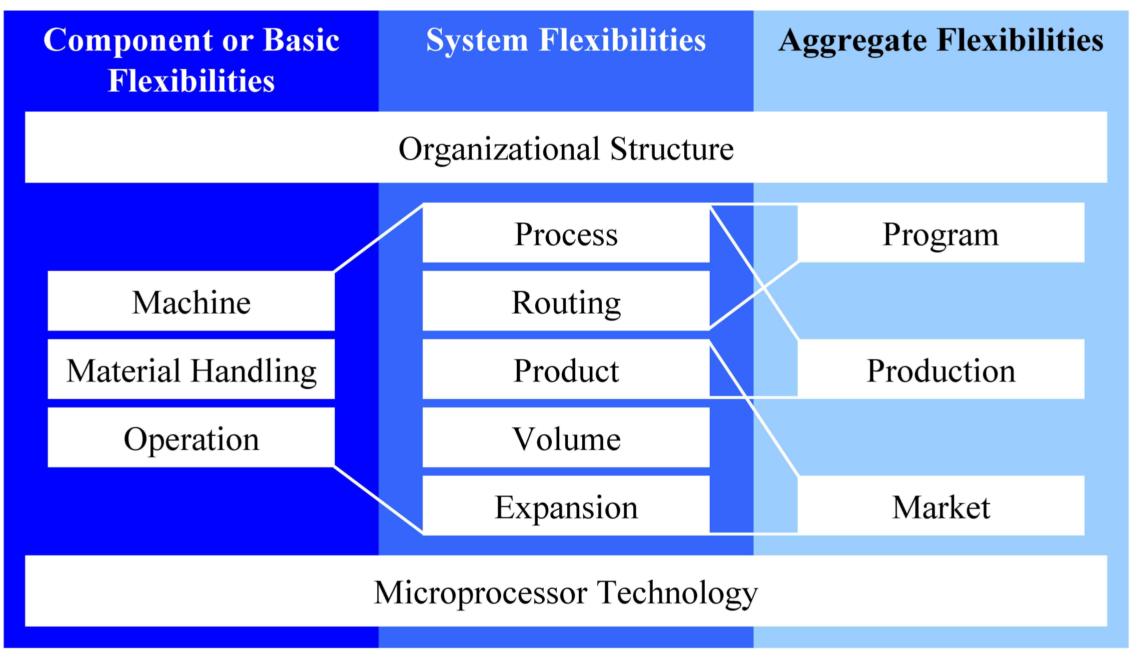

Figure 2-2: Linkages between the various flexibilities

purposes, means, and metrics of the types of flexibilities. While the purposes of flexibility express why it is needed, the means refer to the firm's technological and managerial responses to that need. The metrics, finally, describe how one can compare different levels of a type of flexibility. See Appendix A for an overview table.

Machine Flexibility

Machine flexibility (of a machine) refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another.

A machine can be, e.g, a production machine or an assembly robot (e.g., welding robots in automotive or riveting robots in aerospace industry), etc. Types of operations that the authors have in mind are, e.g. drilling holes up to 5mm, grinding case-hardened steel to specified tolerances, assembling parts of certain shapes and sizes, etc. With regard to the prohibitive effort, it is usually expressed in terms of time and cost.

Purpose Machine flexibility is necessary for other flexibilities, or, in other words, software functions alone cannot help to provide any extra flexibility, if the machines are hard and expensive to change. At its own level, machine flexibility allows smaller batch sizes and results in savings in inventory costs, higher machine utilizations, production of complex parts, shorter lead times for new product introductions, and better product quality realizations in the face of random variations in input quality.

Means Technological sources of machine flexibility are numerical control, easily accessible programs, rule-based languages, sophisticated part loading and tool-changing devices, size of the tool magazine, adaptive control to optimize metal removal, integration with CAD/CAM, etc. Machine flexibility requires considerable attention on the part of management. Operators need to be trained to acquire programming, maintenance, and diagnostic skills.

Metrics Machine flexibility can be measured by the number of different operations that a machine can perform without requiring more than a specific amount of reconfiguration or switching effort. Also, the number of tools or the number of programs that the machine can use, the extent of variations in key dimensional and metallurgical properties of the raw input stock the machine can handle, and the rate at which the machine becomes obsolete when a new product is introduced.

Material Handling Flexibility

Flexibility of a material handling system is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves.

The definition covers loading and unloading of parts, transporting them from machine to machine, and eventually storing them under varying conditions of the manufacturing facility. It also subsumes pallet fixtures, which again determine the degree of freedom available to part loading schedules.

Purpose Material handling flexibility is very important for various system flexibilities under consideration. Having a flexible material handling system increases availability of machines and, thus, their utilization and reduces throughput times. Automated material handling systems, in addition, increase the systems' capabilities of information processing, because the system knows where each part is in the factory.

Means Material handling flexibility can be attained by having transporting devices such as forklift trucks and push carts and an appropriate layout design. In highly automated facilities, devices such as automated guided vehicles, robots, and computer control, which can send parts to new paths in cases of blocking and machine breakdowns, would be needed to acquire material handling flexibility. Having a number of general-purpose fixtures will also increase flexibility[2].

Metrics The material handling flexibility of a given system can be expressed by the ratio of the number of paths that the system can support to the number of paths supported in the whole manufacturing system. Note that this ratio also gives an indication of the inhibition of other manufacturing flexibilities, especially routing

[2]General-purpose fixtures is also one of the key characteristics in the concept of product platforms, see Section 2.5.

flexibility, i.e. without high material handling flexibility of handling systems it is difficult to improve routing flexibility.

Operation Flexibility

Operation flexibility of a part refers to its ability to be produced in different ways.

Operation flexibility is a property of the part, and means that the part can be produced with alternate process plans, where a process plan means a sequence of operations required to produce the part. An alternative process plan may be obtained by either an interchange or a substitution of certain operations by others. Thus, a part that permits operations to be performed in alternate orders or using different operations (i.e., slurry versus wire brush deburr) in an interchangeable fashion would posses operation flexibility.

Purpose Operation flexibility of parts contributes to various system flexibilities, especially the routing flexibility. Operation flexibility of a process allows for easier scheduling of parts in real time and increases machine availability and utilization, especially when machines are unreliable. It is also important when some operations are carried out by external suppliers.

Means Operation flexibility of a part derives from its design. The design should allow the parts to have surfaces that can be produced by various operations. Parts that are assembled from standardized components or parts that are modular are likely to exhibit operation flexibility. Systems such as CAD/CAM, CAPP, and group technology make it easier to design parts possessing operation flexibility.

Metrics Operation flexibility of a part can be measured by the number of different processing plans for its fabrication.

Process Flexibility

Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups.

A major concern regarding process flexibility are switching times. Another preferred term for process flexibility is *mix flexibility* (Gerwin [Ger93]). This is mentioned here not to confuse, but to introduce this widespread expression in the framework used in this thesis.

Purpose The main purpose of process flexibility is to reduce batch sizes and inventory costs. This can be accomplished even when there are shifts in the product mix demanded by the market. It has to be emphasized that process flexibility allows machines to be shared and, thus, minimizes the need for duplicate or redundant machines. Process flexibility helps satisfying the strategic need of being simultaneously able to offer to customers a range of product lines, see also Figure 1-4.

Means Process flexibility of a system derives form the machine flexibility of machines, operation flexibility of parts, and the flexibility of the material handling system composing the system.

Metrics A measurement for process flexibility would be the volume of the set of part types that the system can produce without major setups. One could, perhaps, use group technology concepts to define the set of part types. Volume may be expressed by the number of different part types in the set if they can be counted, and if not, by the range of sizes, shapes, etc. The setup then will be expressed by time and costs.

Routing Flexibility

Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system.

Alternate routes may use different machines, different operations, or different sequences of operations. Typically, these different machines (e.g., lathe and milling machines or two brands of grinders) are capable of essentially the same processes. It should be noted that routing flexibility is different from operation flexibility in the sense that the former is the property of a system while the latter is that of a part. Even a part with a single specified operations sequence, i.e., no operation flexibility, may still be processed using different routes through the system. It is also different from material handling flexibility, which is the property of a specific component of the system. An important aspect of routing flexibility is the systems ability to reroute parts in case of machine breakdown.

Purpose Routing flexibility allows for efficient scheduling of parts by better balancing of machine loads. Furthermore, it allows the system to continue producing a given set of part types, perhaps at a reduced rate, when unanticipated events such as machine breakdowns, late receipt of tools, a preemptive order of parts, or the discovery of a defective part occur. Routing flexibility also facilitates capacity expansion if needed.

Means Routing flexibility comes about by having multipurpose machines, machines with overlapping process envelopes, pooling of identical machines into groups, system control software, versatility of material handling systems, and operation flexibility of parts. Some planned underutilization of machines are needed in order for the system to be able to be rescheduled and maintain the overall production rate in case of a machine breakdown.

Metrics Routing flexibility can be measured by the average number of possible ways in which a part type can be processed in the given system and the ratio of existing number to possible number of links between machines in the given system.

Product Flexibility

Product flexibility is the ease with which new parts can be added or substituted for existing parts.

In other words, product flexibility is the ease with which the part mix currently being produced can be changed inexpensively and rapidly. It should be kept in mind that the addition of new parts will invariably involve some setup. This distinguishes product flexibility from process flexibility. What is required for product flexibility is that the setup does not involve inordinate amounts of time and cost. It should be emphasized that the new parts in the definition above cannot be arbitrary, i.e. product flexibility is bounded.

Purpose Product flexibility allows the company to be responsive to the market by enabling it to bring newly designed products quickly to the market. Since the future product designs are usually unknown, it becomes important to design and develop the production facility to be product-flexible. In markets that are rapidly in flux due to short and uncertain product life cycles, product flexibility along with a sophisticated CAD capability provides a formidable competitive advantage.

Means Product flexibility depends on machine flexibility, material handling flexibility, operation flexibility, efficient CAD/CAM interface, CAPP, group technology organization, use of similar part programming routines, rapid exchange of tool and dies (SMED concepts, etc.), flexible fixtures, product platforms, etc.

Metrics Product flexibility can be measured by the time or cost required to switch from one part mix to another, not necessarily of the same part types.

Volume Flexibility

Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels.

Note that only feasible output levels are under consideration here. Stigler's model with the cost curves can be used to illustrate volume flexibility.

Purpose Uncertainty in the level of demand can impede the strategic objective of increasing and maintaining market share. Volume flexibility permits the factory to adjust production upwards or downwards within wide limits.

Means Volume flexibility can be achieved by going for low variable costs and accepting, perforce, higher fixed costs. Nevertheless, low fixed *and* low variable costs would be the utopian aim. Since the literature about volume flexibility is somewhat confusing, further research about the influence of fixed and variable costs on volume flexibility is made, see Appendix B.

Metrics An obvious measure for volume flexibility would be by the range of volumes in which the firm can run profitably.

Expansion Flexibility

Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed.

The capacity is expressed in terms of output rate per unit time, whereas capability refers to such characteristics such as quality, the technological state, other types of flexibilities, etc. Note that in contrast with volume flexibility, expansion flexibility is concerned with capacity, i.e. the maximum feasible output level. Expansion flexibility makes it easier to replace or add machinery by providing for such possibilities in the original design. Ease in this context refers to the overall effort needed for the expansion. It would include the direct costs, the indirect costs of interruption in production because of the expansion, and the speed at which the expansion can be accomplished. While expansion flexibility targets peak capacity, volume flexibility is the profitable range around a nominal output level, see Figure 2-3.

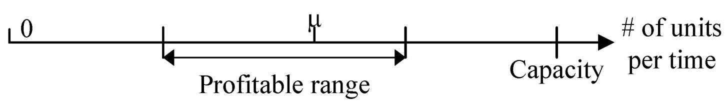

Figure 2-3: Volume and expansion flexibility

Purpose Expansion flexibility is important for firms with growth strategies such as venturing into new markets, since it permits step-by-step adaptation of the system for expansion.

Means Expansion flexibility can be achieved in several ways, such as by building small production units, having modular flexible manufacturing cells, having multi-purpose machinery that does not require special foundation and a material handling system that can be more easily routed, having a high level of automation that can facilitate mounting additional shifts, providing infrastructure to support growth, and planning for change.

Metrics Expansion flexibility can be measured by the overall effort and costs needed to add a given amount of capacity. E.g., the costs for doubling the capacity.

Program Flexibility

Program flexibility is the ability of the system to run virtually untended for a long enough period.

The 'long enough period' period means basically during the second and third shift. If running in such a mode of operation, inspection, fixturing, and maintenance can be performed during the first shift.

Purpose Being able to work untended increases the effective capacity of the production system. Increased understanding of the process required to attain program flexibility results in procedures that can produce products with tighter tolerances and better quality. Thus, program flexibility allows simultaneous improvement in productivity and quality.

Means Program flexibility depends on process and routing flexibilities and on having sensors and computer controls for detection and handling of unanticipated problems such as breakages, part flow jams, etc. Quality control and tool maintenance can be included here too. Program flexibility is a stringent requirement, since it necessitates a thorough understanding of the system; only then can all of the contingencies of the system be coded.

Metrics An obvious measure would be the expected percentage uptime during the second and third shifts. Another usable approach would be a scale of measuring the automation level, similar to Bright [Bri58] who introduced a scale from 1 (lowest) to 17 (highest).

Production Flexibility

Production flexibility is the universe of part types that the manufacturing system can produce without adding major capital equipment.

Minor resources such as new tools may be allowed in order to define the relevant universe. In contrast with product flexibility, note that production flexibility does allow considerable setups but not major capital equipment expenditures. In a way, production flexibility defines the set of existing and potential (or even hypothetical) parts, from which the candidate parts can be drawn as the new parts considered in the definition of product flexibility.

Purpose Production flexibility allows the firm to compete in a market where new products are frequently demanded. Production flexibility minimizes the implementation time for new products or major modifications of existing products. On the operational level, it permits an increase of part families and allows the firm to mitigate market risks via diversification.

Means Production flexibility depends on the variety and the versatility of the machines that are available, the flexibility of material handling systems in use, and the factory information and control system. Thus, production flexibility derives from the capability of aggregation of the flexibilities of the machines and material handling systems. The system can perform all the operations that are inherent in the machines of the system. But, in terms of part types that the system can make, production flexibility is more than the sum of the parts that each individual machine can make.

Metrics A possible measure for production flexibility is the size of the universe of parts the system is capable of producing. However, since production flexibility is, in some sense, a 'long-run product flexibility' its valuation can be obtained in a fashion similar to that used by Jaikumar [Jai86] to determine product flexibility. I.e., it can be measured by certain shadow prices in an appropriate mathematical programming problem formulated for a longer term.

Market Flexibility

Market flexibility is the ease with which the manufacturing system can adapt to a changing market environment.

This concept emphasizes the importance of market orientation in manufacturing. Especially in rapidly changing markets, the interface between production and marketing functions becomes crucial. Lack of flexibility inside the firm can -at least partially- be compensated by the supply chain. It is obvious that market flexibility of the manufacturing system complements its production and program flexibilities.

Purpose Market flexibility is important for a firm's survival in environments that are constantly in flux. Environments change because of rapid technological innovations, change in customer tastes, short product life cycles, uncertainty in sources of supply, etc. Market flexibility allows the firm to respond to these changes without seriously jeopardizing the business.

Means As markets change, the manufacturing system may be required to process new products, cope with fluctuating production volumes, and even to undergo capacity changes. Thus product, volume, and expansion flexibilities contribute to market flexibility. Market flexibility requires that the process of production planning and inventory controls be closely integrated with such marketing functions as market forecasts, product development, and customer relations.

Metrics Market flexibility can be expressed as a weighted measure of efforts in terms of time and costs required to introduce a new product, to increase and decrease production volume by a specified amount, and to add a unit of capacity. Sometimes, however, capacity can only be increased in discrete steps.

Linkages between various Flexibilities

Figure 2-2 summarizes the linkages between the different types of flexibilities that have been reported to exist. Three levels of flexibility exist: the component or basic level (i.e., flexibility of a machine), the system level (i.e., flexibility of a production system), and the aggregate level (i.e., flexibility of a whole manufacturing plant). The figure indicates that flexibilities of components contribute to the various flexibilities of the system. These in turn influence the aggregate flexibility as shown. Viewed from another perspective, the firm's manufacturing strategy dictates the extent of system flexibility and, in turn, of component flexibility that the firm must possess. It has to be emphasized that the structure of organization and microprocessor technology underlies all of the flexibility. Ideally, flexibility at the component and system level is implemented based on a market-driven flexibility at the enterprise level.

2.2.2 Other approaches

Some other approaches for classifications of flexibility are briefly presented here. They should only act as 'thought-provoking impulse' and will not be discussed in detail. They are arranged in order of their date of publication.

Gupta and Somers

Gupta and Somers [GS92] develop an instrument for measuring and analyzing manufacturing flexibility. They identify 34 items affecting manufacturing flexibility from the literature and create a preliminary instrument to measure them, e.g. 'Time required to introduce new products', 'Time required to add a unit of production capacity', 'Number of new parts introduced per year', etc. During the analysis they reduce their list to 21 items. The results of a survey of 269 companies then are manipulated using factor analysis techniques to create a construct of 9 principal types of flexibility based on the 21 lower order items: volume, programming, process, product and production, market, machine, routing, material handling, expansion and market flexibility. Figure 2-4 shows the result of their research. Even though, the figure does not show any interactions between the different types of flexibilities, it can be seen which specification attribute has influence on which type of flexibility. An other question is, if a single input variable only influences one type of flexibility or if mul-

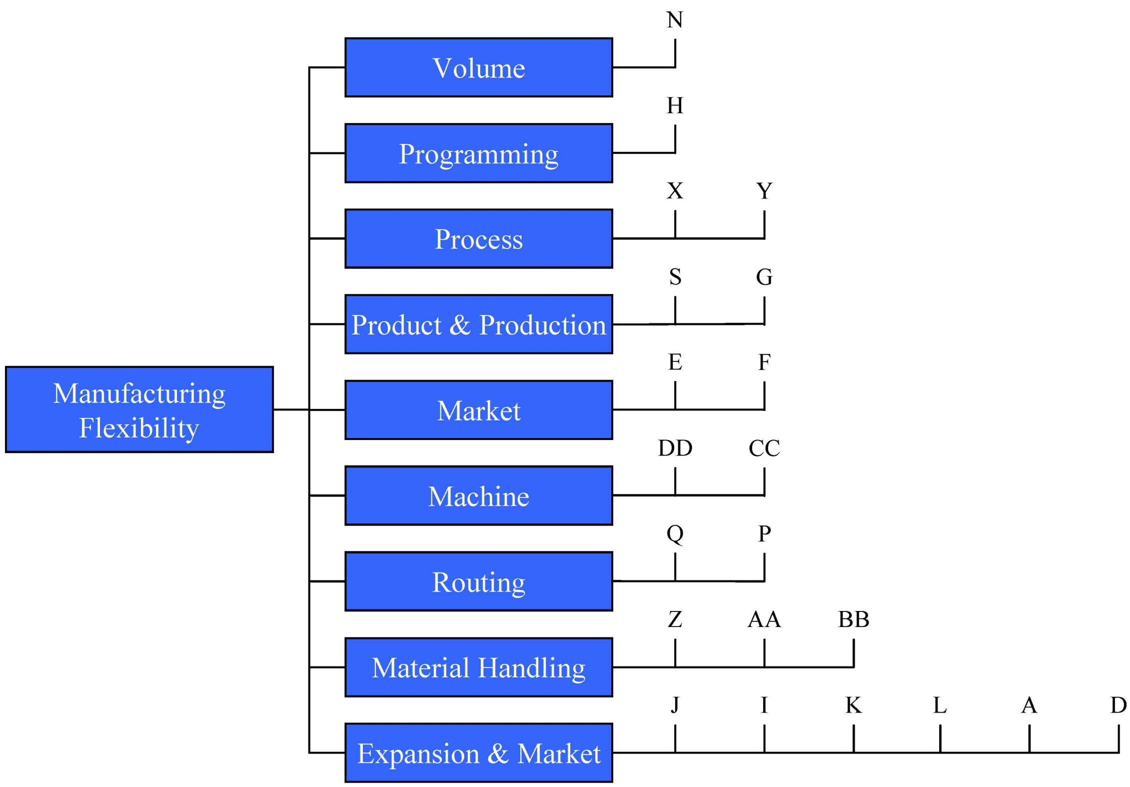

Figure 2-4: A model for measuring manufacturing flexibility

tiple entries would be possible. The 21 manufacturing variables discussed are found to affect the corresponding type of flexibility in a way that flexibility is high if:

A Time required to introduce new products is extremely low.

D Time required to add a unit of production capacity is low.

E Shortage cost[3] of finished products is extremely low.

F Cost of delay in meeting customers' orders is extremely low.

G Size of the universe of parts the manufacturing system is capable of producing without adding major capital equipments is extremely large.

H The manufacturing system is capable of running virtually unattended during the second and third shift.

I Cost of doubling the output of the system is likely to be extremely low.

J Time that may be required to double the output of the system is likely to be extremely low.

K The capacity of the system can be increased when needed with ease.

L The capability of the system can be increased when needed with ease.

N The range of volumes in which the firm can run profitably is extremely high.

P Cost of the production lost as a result of expediting a preemptive order is extremely low.

Q Decrease in throughput because of a machine breakdown is extremely low.

S Number of new parts introduced per year is very high.

X Changeover cost between production task within the current production program is extremely low.

Y The ratio of the total output and the waiting cost of parts processed is extremely low.

Z The ability of the material handling system to move different part types for proper positioning and processing through the manufacturing facility is extremely high.

AA The ratio of the number of paths the material handling system can support to the total number of paths is very high.

BB The material handling system can link every machine to every other machine.

CC The number of different operations that a typical machine can perform without requiring a prohibitive time in switching from one operation to another is very high.

DD The number of different operations that a typical machine can perform without requiring a prohibitive cost in switching from one operation to another is very high.

The construct later is tested on a further 113 companies and is found to exhibit 'adequate reliability and validity'.

[3] Costs for products in stock that can no be sold anymore

Nilsson and Nordahl

The objective of the research of Nilsson and Nordahl ([NN95a] and [NN95b]) is the development of a framework for manufacturing flexibility which shows how to obtain consistency from manufacturing strategy to the resource characteristics in the production system. The framework provides guidance on how to analyze and develop manufacturing flexibility in a corporate decision making context.

Their model makes a clear distinction between internal and external factors. The expression *external flexibilities* is used for issues concerning flexibility in the relationship between the company and the context outside the company. Two groups of external flexibility exist according to the authors: *output flexibility*, which are found in the relationship between the company and its customers, and *input flexibility*, which are found in the relationship between the company and its suppliers. Thus, external flexibility is what the customers demand from their suppliers and what the supplier can supply.

Flexibility located within the boundaries of the company could be named *internal flexibility*. In other words: internal flexibility is how a company, internally, can accommodate its production facilities in order to fulfill the demand for external flexibility. Internal flexibility has two levels: the system level and the resource level.

By combining those two major groups of flexibility, Nilsson and Nordahl build a framework that consists of three distinct levels: (1) strategic, where input and output flexibilities are defined at the marketplace between the company and its suppliers or customers; (2) production system, where the characteristics of the production system are defined on a tactical level; and (3) production resource, where the resource characteristics are defined on an operational level.

The translation from one level to another is made via a transformation matrix. So there are three matrices, input↔system, system↔resource, and system↔output. The matrices are used to create concordance between the flexibilities at the different levels. An example of such a transformation matrix can be seen in Table 2.2. In each square the consequences for the next level are articulated, e.g. 'The requested volume flexibility needs lower batch sizes in order to be able to deliver faster and in smaller quantities.' Every matrix is worked through and existing gaps between target

Output flexibilities / Systems characteristics	Product flexibility	Volume flexibility	Conclusions
Capacity		Higher upwards volume flexibility is needed	
Batch sizes	Batch sizes of 50 units must be feasible for all products		

Table 2.2: Example for a translation matrix, e.g. output↔system

and actual situation can be identified. Action then can be taken to reduce that gap. However, it may not be quite feasible to close the entire gap. Counteracting demands may make it impossible to fulfill all the demands, thus making it necessary to rerun the process.

Shewchuk and Moodie

Shewchuk and Moodie ([SM97] and [SM98]) present a framework as presented in Figure 2-5 (reproduced from [SM97]). This framework consists of three axis: primitive flexibility types, level of requirements specification, and time frame.

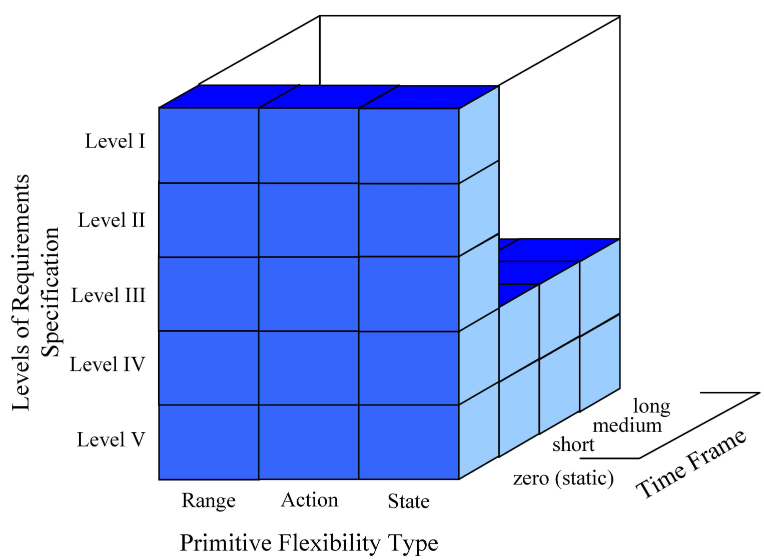

Figure 2-5: Framework for classifying flexibility types

The authors define the different types of primitive flexibility as following. The *range flexibility* is the total envelope of capability or range of states which the production system or resource is capable of attaining. With *action flexibility* they understand the ease (in terms of cost, time or both) with which changes can be made within the capability envelope. The third primitive type of flexibility, *state flexibility* is defined as the capacity to continue functioning effectively despite change (and might be comparable to robustness).

The second axis, level of requirement specification, contains five levels. At level I, the functional requirements for the manufacturing system, the manufacturing system solution space, and the capital constraint for the system design are all given. Level I measures then indicate how flexible the system is compared to what it could be for the given constraints.

At level II, the manufacturing system and the product solution space are given. Level II measures indicate the ability of the system to process the universe of products which are deemed possible for the manufacturing environment.

The requirements specification variables that are given at level III are the manufacturing system, product solution space, and product environment. Level III measures indicate the ability of the system to process those products which are planned, anticipated, or likely to be encountered in the manufacturing environment.

At level IV, the manufacturing system, product solution space, product environment, and production solution space are all given. Level IV measures indicate the ability of the system to handle all possible production scenarios for any set of products which are planned, anticipated, or likely to be encountered in the manufacturing environment.

The requirements specification variables given at level V are the manufacturing system, product solution space, product environment, production solution space, and production environment. Level V measures indicate the ability of the system to handle those production scenarios which are planned, anticipated, or likely to be encountered for any set of products which is planned, anticipated, or likely to be encountered in the manufacturing environment.

The second axis seems to be the most difficult to understand. Therefore, Shewchuk and Moodie give some examples. At level I they locate routing, machine, and expansion flexibility. At the second level, production, and process flexibility are located. On the third layer they put product flexibility. Volume flexibility is placed at level IV, and at level V they locate market flexibility. The authors add some more, but these types of flexibility are not congruent with the definitions given above and are therefore not mentioned here.

The time frame constitutes the third axis. It refers to the time interval over which the flexibility measure is calculated. The basic differentiation is between static and dynamic measures. The latter can be further divided in some manner based upon interval length.

In the resulting framework (see Figure 2-5), at each blue cube in the framework, flexibility types having common attributes can be located. With the help of this framework different types of flexibility can be compared according to measurable indexes and can be represented graphically. It is unclear why flexibilities at levels I to III only can be in the static time frame, but probably, the kind of framework may be useful for further research.

Koste and Malhotra

Koste and Malhotra, see [KM99] and [KM00], define four constituent elements of flexibility: range-number (R-N), range-heterogeneity (R-H), mobility (M), and uniformity (U). These elements can be applied to consistently define different types or dimensions of flexibility. On one side, they capture the domain of flexibility. On the other side, these definitions can be used to generate scale items, thereby facilitating the development of generalizable manufacturing flexibility measures. With R-N the authors count the number of possible options which a system or resource can achieve, the higher R-N the bigger the flexibility. The second variable, R-H, indicates the degree of difference between the options of a system, i.e. the versatility of a system, the greater R-H the bigger the flexibility. Koste and Malhotra use M to express the ease with which the organization moves from one state to another (in time and cost), the greater M the bigger the flexibility. The last parameter, U, stands for the similarity of the performance outcomes within the range, the higher U the bigger the flexibility. Then, the authors describe different types of flexibilities by defining them to different levels of one or more of the four elements mentioned above.

Suarez et al.

Suarez, Cusumano and Fine, see [SCF95], use only four types of flexibility. These are mix flexibility (equal to Sethi and Sethi's process flexibility), new product flexibility (product flexibility), volume flexibility, and delivery time flexibility (mixture of volume and market flexibility). They state that all other types of flexibility are variants of these four. But, more important than the argument about definitions are their *Implications for Managers*: In a survey of 31 plants in the printed circuit board industry they conclude that

> 'Flexibility in our sample has much more to do with non-technology factors than with technology itself. (...) In fact, the plants with more programmable automation ended up being the less flexible plants. (...) Before buying the latest available technology, managers would be better off concerning on maximizing the potential flexibility in their current organization and technology. At least in the short term, it seems possible for managers to squeeze a lot of flexibility from their existing equipment. (...) Having flexibility included in the strategy concepts and frameworks will help managers to be more sensitive to the importance and challenges of managing flexibility. There is no question that today's world demands more flexibility; the real issue is being able to understand and manage it strategically.'

According to the authors, there are six main factors that affect flexibility implementation: production technology, production management techniques, relationships with subcontractors and suppliers, human resource management, product development process, and accounting and information systems. Finally, they warn that 'it is not always beneficial to increase flexibility, of course, if it also increases costs or decreases quality'.

2.3 Valuation

Two main methods are discussed in the literature on how to value flexibility. One is the net present value (NPV) method and the other is the concept of real options.

Net Present Value

The first method, NPV, is discussed by Alvarez Gil, see [Alv94]. She emphasizes that 'no matter how relevant changes in flexible manufacturing equipment can be for a firm's survival, if they are not financially justified, the investment will not get the approval and the go-ahead; the justification process is largely strategic in nature but must also involve financial issues'. The author's work lies mainly in connecting flexibility with monetary values. The rest then is simple capital budgeting which will not be discussed here.

Alvarez Gil uses the framework of Gupta and Somers ([GS92]), see above, to determine the operative variables (A to DD) that influence the different types of flexibilities. In order to translate these operative variables into financial variables, it is necessary to identify first the types of flexibility which have relationships with various decisions. This can be achieved by classifying the types of flexibilities according to their impact on long-term and short-term decisions. Conventionally, long-term decisions are financially associated with long-term capital budgeting, while short-term decisions are associated with cash management and treasury budgeting.

Further, design and operational flexibility are distinguished. Design flexibility influences the strategic type of production technology investments that a firm should accomplish. Short-term decisions concerning flexible technology implementation and control are involved with the operation of the plant and linked to operational flexibility. This differentiation between long and short-term flexibilities and capital and cash budgeting techniques allow the ex-ante and ex-post justifications of investments in flexible equipments.

Tangible and quantifiable benefits of increased design flexibility must be defined, such as 'increase in market share', 'increase in sales volume', 'reduced product development time', or 'direct labor savings'. The economic value of these benefits can be known with certainty or at least up to a probability distribution. If a direct linkage between those benefits and the types of flexibilities can be found, then a group of benefits can be formed that relates to design flexibility. For Alvarez Gil those are volume, process, expansion & market, machine, and product & production flexibility. All other flexibility types, consequently, relate to operational flexibility. That are material handling, routing, programming, and market flexibility. This second group is very difficult, if at all, to estimate ex-ante their tangible benefits. However, it can be considered to comprise intangible benefits like 'increased ability to quickly enter new markets', 'synergy with other equipments', or 'better scheduling or work flow'.

A capital budgeting calculation is always a difference calculation, see Seiler [Sei99]. Normally, the difference between the situation with and without the planned investment is considered.

The next step is to evaluate changes in the mentioned benefits, if an operational variable is changed. I.e., analyzing variable A (time required for introducing new products) it can for example be found, that decreasing that time by 1% will increase market share by 2%. This is quantifiable and since A influences expansion & market flexibility (see Figure 2-4) the value of an increase of that kind of flexibility can be measured financially. All affected operational variables have to be analyzed in this fashion and, thus, the flexibilities' value of a new system (machine, layout, organization, etc.) can be quantified. This flexibility benefit finally is entered in the NPV or IRR calculation and, thus, takes part in the valuation of a new system.

Real Options

The second group, valuing flexibility with the concept of real options, is discussed by Bengsston and Olhager ([Ben01], [BO02a], [BO02b]). A flexible system gives numerous options to management and these could, i.e., be constituted by the ability to increase or decrease capacity, switch between products and switch between input material. Hence, flexibility gives management some degrees of freedom to take advantage of outcomes better than based on fixed and uncertain predictions alone and simultaneously provides the ability to reduce losses. Such options must, of course, have a value to companies. When using real options for capital budgeting purposes it is possible to take flexibility options into account in the valuation process.

The evaluation procedure for valuing flexibility is not straightforward, since flexibility may be regarded as the potential behavior of the manufacturing system to adapt to future environmental changes, rather than the flexibility that has been demonstrated historically. This insight opens up for new valuation approaches that do not stem from the manufacturing arena. One such approach is the use of option pricing theory. The apporach is called 'real options' when applied to non-financial, or 'real', assets. The action space that the flexibility property of the manufacturing system spans can be interpreted as a set of options. Then, the flexibility potential of a system can be evaluated using real options.

Consider a simple example of flexibility, i.e., a firm has the option to produce if revenue exceeds variable cost. The underlying asset is represented by the revenue, which is uncertain, and the exercise price by the variable cost which are known. An important thing that differs between real and financial options is the underlying asset. In the case of financial options, the value of the underlying asset is often easily observed in the financial markets, but, in the case of real options whose value, e.g., depend on revenues, it is much harder to observe and gather data.

The authors define a new type of flexibility, product-mix flexibility, defined as 'the ability to change relative production quantities among the products in a product mix. This is a combination of Sethi and Sethi's product, process, and production flexibilities.

Then they build a model using real options for the valuation of product-mix flexibility. They made the following assumptions regarding the options and the payoff:

1. Production decisions are taken at pre-set points in time $T_k, k \in [1, K]$ and

$T_1 < T_2 < \ldots < T_k$. The time between any two pre-set points in time is allowed to vary.

2. If the value of the demand of product $i, i \in [1, N]$, does not exceed any set-up cost, SC_{il}, of assembly line $l, l \in [1, L]$, no production of product i will take place.

3. If total demand is higher than actual total capacity C_{max}, a selection among products takes place with the objective to assign products to assembly lines so as to maximize profits.

4. If production is constrained to produce the total demand of product i, D_{ik} due to capacity limitations but is able to produce the quantity Q_{ilk} such that the value of the produced quantity exceeds set-up costs, then the product is a candidate for production.

5. The price of product i, P_i, is stable and exogenously given. Variable costs VC_{il} are fixed, and set-up costs are also stable but they may differ between assembly lines.

6. No inventory is considered.

7. Demand that cannot be satisfied is considered as lost sales. Thus, back-orders are not allowed.

These assumptions imply the following Equation 2.1, which models the options and the pay-off of an optimal production decision at time T_k:

$$V_k(T_k) = \max\left\{\sum_{l=1}^{L}\sum_{i=1}^{N}\max\left[(P_i - VC_{il})\cdot Q_{ilk} - SC_{il}\ ,\ 0\right]\right\} \tag{2.1}$$

s.t.

$$\begin{aligned} \sum_{l=1}^{L} Q_{ilk} &\leq D_{ik} \\ \sum_{i=1}^{N} Q_{ilk} &\leq C_{max}^{l} \end{aligned}$$

Based on Equation 2.1, a production system can be regarded as a portfolio of European options to produce since there are no interdependencies between options in different periods. Investing in a system will give us numerous options to produce so as to maximize contribution margin, but to make a correct investment decision, investment and fixed costs must be considered. It should be noted that set-ups are considered as set-up costs whereas set-up times are not included explicitly.

To estimate the value of the option $V_k(T_k)$ with exercise date T_k, the following procedure is carried out by the authors:

1. Simulate 'risk-free' demand, under the Q-measure, for all products i giving a demand vector D.

2. For a given D, optimize production so as to maximize the value of the production schedule.

3. Perform the steps above n number of times.

4. Estimate the expected value of the option, i.e., the mean of the pay-off over all simulation runs.

5. Discount the expected value with the risk-free rate to get the present value of the option.

This procedure is repeated to all available options and an aggregate value of all options can thereafter be determined.

2.4 Strategies

One of the most meaningful articles about strategies for flexible manufacturing is written by Gerwin, see [Ger93]. To explore the links between strategy and flexibility, it is useful to work within a broad context, as suggested by the conceptual framework illustrated in Figure 2-6, reproduced form Gerwin. He works out four generic strategies which deal with flexibility. They are: adaptation, redefinition, banking, and reduction, see Table 2.3 reproduced from Gerwin.

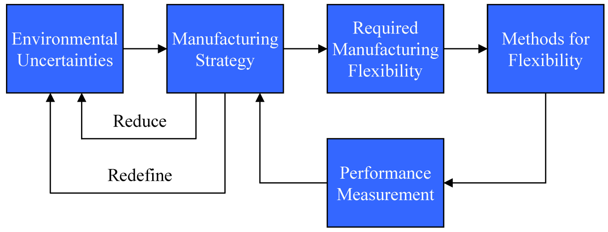

Figure 2-6: Conceptual framework - links between strategy and flexibility

Strategy	Posture	Impact for Flexibility
Adaptation	Defensive	Requires flexibility
Redefinition	Proactive	Requires flexibility
Banking	Defensive/Proactive	Requires flexibility
Reduction	Proactive	Reduces need for flexibility

Table 2.3: Generic flexibility strategies

Adaptation represents the path in Figure 2-6 from uncertainty to strategy to flexibility and beyond. This defensive approach incorporates the traditional use of flexibility.

An enterprise, however, may try to *redefine* market uncertainties as indicated by one path in the model emanating from strategy to uncertainty and to flexibility. A firm can encourage customers to see the benefits of shorter lead times or more frequent new product introductions and then provide these higher levels of service through superior manufacturing flexibility.

A company may decide to *bank* flexibility, that is hold it in reserve to meet future needs. In this sense flexibility is an investment which creates options for a firm. It may eventually be used defensively to adapt to a sudden dramatic change in market conditions. One example is the 'surge capacity' maintained by military contractors to quickly increase production volume during a national emergency. Alternatively, a reserve of flexibility may be employed proactively to redefine competitive conditions.

Reduction[4] is a proacive approach which is not based on the use of flexibility, although it has important implications for that concept. It represents a path leading form strategy to uncertainty and to flexibility. A company may reduce environmental

[4]Since flexibility is the evolutionary level of robustness, see Section 1.1.1, a reduction strategy can be seen as strategy for robustness.

uncertainty through, e.g., long-term contracts with customers and suppliers, design for manufacturability, preventive maintenance, and total quality control.

To analyze whether more or less flexibility is needed in a particular setting it is necessary to distinguish between required, potential, and actual flexibility for each aspect, such as range or time, of the identified flexibility types. Three main misalignments are established: required flexibility is greater than potential flexibility, potential flexibility is greater than the actual, and potential flexibility is greater than the required.

This is followed by an instruction how to proceed for implementing desired changes in flexibility. First, the flexibility dimensions that require investigation must be defined. Second, the gaps between actual and target level of flexibility have to be measured. Third, methods how to close these gaps are to be selected. Fourth and last, there should be the start for further, continuous assessments.

2.5 Interviews

In addition to the literature review about manufacturing flexibility, some interviews were conducted to get some practical insight.

Three firms in Switzerland were visited. In advance of the visits, a questionnaire was sent to those firms, see Appendix C. All three enterprises are either suppliers to the aerospace or automotive industry and have a division in which parts are produced using forming technology.

Firm A is a small family-owned enterprise with about 20 employees. It is a small subcontractor to several firms and manufactures complex (added value about 80%) parts, most of them in stainless steel, in quantities of 5,000 to 50,000 (cumulated over the whole products' lifetime). The firm faces uncertainty mainly in the dimension of huge fluctuations of the demand per period. So, a major concern is volume flexibility. For the firm's CEO, good and loyal employees are very important, because this allows adding shifts easily. In order to not to let the variable cost get out of hand, the firm runs an *annual working time* model. I.e., people work more if needed, but do not get more money, and work less if a lower capacity is needed, but do not earn less money. At the end of the year the balance of work time is examined and differences are either cleared financially or by additional leave days. For dealing with product flexibility, firm A uses old and multi-usable machinery and tries to reduce the need for dedicated tools. Existing parts are hardly ever redesigned, thus, costs for changing tools can be reduced to a minimum.

Firm B is big company with about 2,500 employees in its aerospace division. It produces parts for civil and military airplanes. Uncertainty in design is very high over time, therefore dedicated tools must be used as little as possible. But, since in the aerospace industry many parts are made by deep drawing processes, the firm attempts to manufacture as many parts as possible using its fluid cell press (hydro forming), on which tool costs are clearly below the ones of traditional deep drawing machines. Nevertheless, latest investments have been made in high-speed machining rather than in forming technology. Due to the low volumes multifunctional machines are very important. The risk for obsolete tools and machinery lies completely on the suppliers' side. Volume flexibility is embedded in the same way as in firm A, with additional shifts and the concept of annual working time. Routing flexibility is nearly zero, because all manufacturing processes are approved by the firm's customers and must not be changed without a new approval process. Process flexibility, on the other hand, is at a very high level. The firm can produce profitably with lot size one, and, thus, react quickly to changes in demand or preemptive orders. Also, there is no inventory, which is a big advantage for the production manager. During the offer phase in the sale process the firm can influence the part design, but after the validation, it is very difficult to make design changes, e.g., to improve production profitably. The representatives of firm B emphasize, that is has been more difficult to teach the employees flexibility than to implement it technically.

Firm C competes, among other things, in the automotive industry. It employs about 500 people and is 'just big enough to be accepted as a tier one or tier two supplier'. The firm's representative states that in the automotive industry there are only few risk for the suppliers. The firm gets binding prognoses from its customers, and, if the demand is lower than the forecast, the customer will pay for investment in tools and other dedicated manufacturing devices. This is important because price-competition is extremely high. Getting an order or not, is the matter of fractions of cents during the offer phase. Since the production volumes are very high and parts remain stable for several years, machine flexibility is usually kept at a low level. Considering forming technologies like die cutting, deep drawing, and stamping, state-of-the-art output rates are between 30 to 80 parts per minute (for bigger parts) and 250 to 300 parts per minute (for small parts). Slower processes like hydro forming are too slow. Nevertheless, the machines' utilization ratios are at a rather low level in firm C. This is astonishing because the presses (without the tools) are highly flexible. But, as in the aerospace industry, the manufacturing processes in the automotive branch are validated and certified by the customers. So, routing flexibility is very low. One tool must only be used for one product and together with a determined press. Otherwise, the manufacturing process has to be re-validated. For absorbing fluctuations in demand, the firm also uses the concept of annual working time. If demand exceeds the firms' capacity it may have the possibility to outsource the whole production of a part. During the product development process, the firm is in tight cooperation with the customers. The representative of firm C emphasizes that, feasibility is the major concern, not flexibility.

Concluding the visits of these three firms, two groups can be made. Characteristics for the automotive industry are:

- high volumes,
- high automation levels,
- high quality of predictions for next years volumes, and
- low levels of flexibility.

In contrast, in the aerospace industry, it is exactly the other way round. There, one will encounter

- low volumes,

- low automation levels,
- low levels of predictions for next years volumes, and
- high levels of flexibility.

A fourth firm was visited in New Hampshire, U.S.A. It is a supplier to the aerospace and astronautics industry. The astronautics industry, of course, has even lower volumes than the aeronautical branch. So, this company manufactures its product by aluminum investment casting in a ceramic shell. The fraction of manual work is extremely high, and, thus, volume flexibility is very low. But other types of flexibility, such as machine (casting implements), material handling (humans), process, routing, product, and market flexibility are at high levels.

At last an interview was conducted with Dr. Daniel E. Whitney, Senior Research Scientist at MIT's Center for Technology, Policy & Industrial Development. His major statements are summarized here. He emphasizes that for achieving flexibility high technology is not the most important aspect. Highly skilled workers and reliable data processing/data management system come before the big capital investment. He adds that 'variety and flexibility is driven by the parts' sizes'. Flexibility is easier to reach for smaller parts than for bigger parts, since manufacturing and assembly equipment has about 100 times the size of the parts it produces. A big deal in the automotive industry (car assembly, not comparable to the firms mentioned above) is the problem of the fixtures. Being able to work with multi-usable fixtures is a major driver for the introduction of the platform concept. So, one can distinguish flexibility at the parts manufacturing level versus flexibility at the assembly level. Dr. Whitney acknowledges that flexibility is also capital driven. Thus, the investment has to be made flexible, e.g. for welding robots.

2.6 Summary

The scope of this chapter is twofold. First, it gives theoretical and practical insights into the state-of-the-art of manufacturing flexibility. Second, it acts as a base for further chapters of this thesis.

Eleven different types of flexibility are defined and discussed. These are machine, material handling, and operation flexibility at the base or component level flexibilities. Process, routing, product, volume, and expansion flexibility are arranged to system flexibility. The last group, aggregate flexibility, consist of program, production, and market flexibility. Other classification schemes than the one made by Sethi and Sethi are introduced and briefly explained. Two concepts on how to value flexibility are presented in order to round out the to literature review.

The results of the interviews show further aspects of flexibility and its environment in today's firms. Two groups with typical characteristics for the automotive and the aerospace industry are derived.

It is obvious that not all current concepts of manufacturing flexibility can be discussed in this chapter. A complete list of all references is contained in the Bibliography at the end of this report.

Nevertheless, in this chapter it is shown that 'manufacturing flexibility can be viewed as a multidimensional concept rather than as an independent variable that can be defined and measured in isolation' (Beach et al. [BMP+00]).

Chapter 3

The Lever Problem

The following 'case study', referred to as 'The Lever Problem' should first act as a simple motivating example to show and explain the fundamental flexibility problems. The lever problem is examined in detail and expanded as the core part of this thesis. The analysis methodology developed for this example is generalizable to other situations.

3.1 The Case

You are the Chief Technology Officer (CTO) of a small manufacturing firm. Assume that you manufacture and sell simple levers A, B, and C with two holes each as shown in Figure 3-1. The company currently offers this family of three levers at

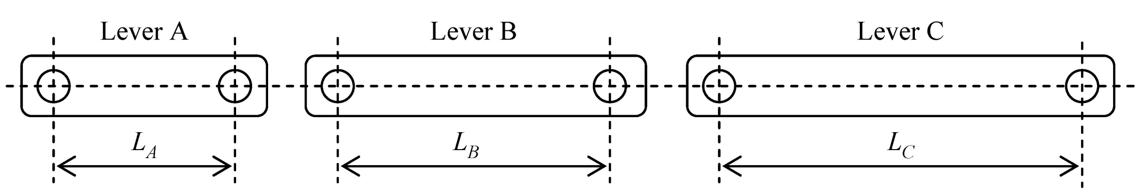

Figure 3-1: Three metal levers: A, B, C

different lengths: $L_A = 0.5 < L_B = 0.75 < L_C = 1.0$. The lengths have been determined by the marketing department, but might be subject to change in the future based on shifting customer preferences. Currently the company is manufacturing and selling the following number of units per year: S_A = 200,000, S_B = 300,000, and S_C = 100,000. These sales numbers strongly fluctuate from year to year. To simulate demand uncertainty, the model of geometric Brownian motion (GBM) can be used, see de Weck et al. [ddC03]. This model is commonly used in the financial community to simulate the price of a stock, P. The discrete-time version of this model is given by Equation 3.1:

$$P_{t+1} = P_t + S_t(\mu\Delta t + \sigma\Gamma\sqrt{\Delta t}) \tag{3.1}$$

P represents the current stock price, Γ is a random variable with a standardized normal distribution and Δt the time step of the discretization. μ is the expected return per time unit on the stock and σ, mathematically the standard deviation, stands for the volatility of the stock price [ddC03]. In Figure 3-2 the fluctuation in the daily demand for the current year is represented. Assuming that the demand of

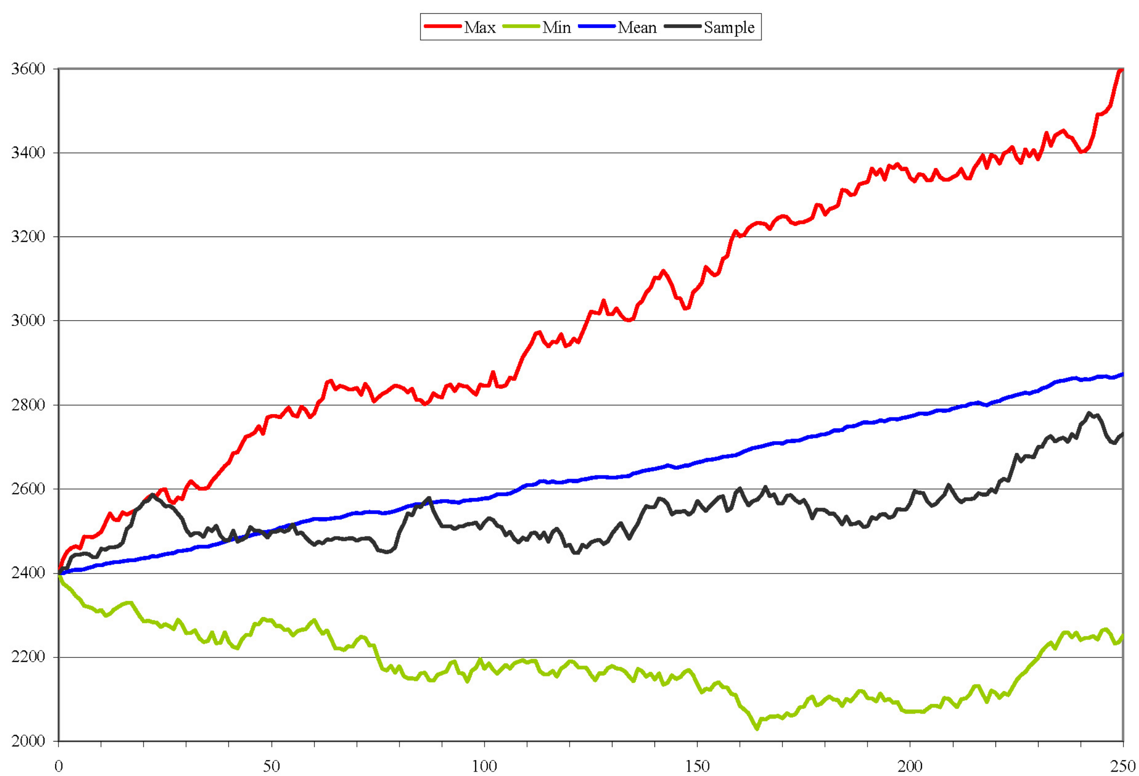

Figure 3-2: Brownian motion, D(0)=2400, μ=0.16, σ=0.3

one workday is $\frac{1}{250}$ of the demand of the year (600,000), the initial value is set to 2,400. μ is set to 0.16 according to the expected increase in sales of 16% for next year (see below). The (daily) volatility σ is set to 0.3 which corresponds to the volatility used in the simulation in Section 3.2.3. In Figure 3-2 the result of 50 simulation runs of the GBM is shown. The four trajectories have the following meaning: The nearly straight one describes the course of the mean value over the 50 results of every day. The top and the bottom display the maximum and minimum demand, respectively, of every day over the 50 runs, i.e., all possible data points are in-between the minimum and the maximum curve. Finally, there is one line that acts as an example for a possible demand trajectory over the year.

To come back to the task of the lever problem, lever A is sold for \$1.00 per piece, lever B for \$1.50 per piece and the price for lever C is \$2.00 per piece. See also Table 3.1. No volume discounts are granted.

Part	Length	Price	Volume
Lever A	0.500	\$ 1.–	200,000
Lever B	0.750	\$ 1.50	300,000
Lever C	1.000	\$ 2.–	100,000
Total			600,000

Table 3.1: Current products

The current manufacturing process is stamping, which requires a special, dedicated tool (die) for each part A, B, and C. Each tool has an estimated lifetime of 1,000,000 stampings and all of them have been newly fabricated at the beginning of the current year. The investment cost of the stamping machine is \$5,000,000, the lifetime of the machine is 10 years.

How can the design or manufacturing of these parts be improved to make the overall system more flexible and competitive in the face of future geometry and demand uncertainties? You contact the marketing, engineering and manufacturing departments to come up with a solution to this problem.

The marketing department returns with the following information: There is a 50% chance that next year's parts will be the same as this year's. There is a 25% chance that a new part D with $L_D = 0.875$ will be added to A, B, and C. There is a 25% chance that an entirely new lever product line α, β, and γ with $L_\alpha = 0.4$,

$L_\beta = 0.8$, and $L_\gamma = 1.2$ will have to be developed to replace the current lever family. The expected sales volumes for next year are up by 5%, 25% and 15% for A, B and C, respectively but are subject to uncertainty. Sales volumes for α, β, and γ would fluctuate uniformly between 50,000 and 500,000 per part. This statement captures both demand and product specification uncertainty.

The engineering department suggests changing the design of the levers so that it becomes easier to change their length. Two competing designs have been suggested by engineering (see Figure 3-3). The first design cuts the lever into two pieces and

Figure 3-3: Two competing designs for imparting lever (product) flexibility

adds a set of holes at fixed locations. The two parts are partially overlapped and riveted together to achieve the desired length. The second design also uses two parts, but introduces a slot in the second part and connects the parts with a wing nut. The first design allows some discrete flexibility for the manufacturer to choose the length but adds complexity (two parts instead of one) and some costs (addition of the riveting process). The second design gives flexibility to the customer, but adds weight (wing nut) and complexity to the part. It is unclear whether the customer will be willing to accept the new design and what the exact impact on the manufacturing costs (fixed and variable) and profits will be.

The manufacturing department has been silent on this issue for two weeks. They have been informally discussing some ideas such as modular stamping dies, only manufacturing lever B and outsourcing A and C, etc... but it is obvious to you that they need external help in thinking how parts A, B, and C could be manufactured by embedding flexibility in the process, rather than in the product as shown in Figure 3-3.

3.2 Approach

The solving of this problem will contain four major steps, see Figure 3-4. They are:

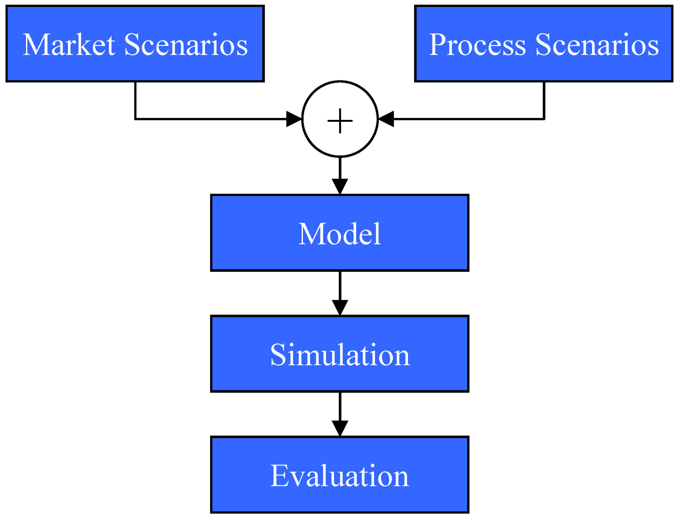

Figure 3-4: Steps in the approach to solve the lever problem

1. Building of a *market scenario* for every possible market evolution as described in the case. Such a scenario must provide information from outside of the firm. It contains the number of different products, their expected sales volumes, geometry data (in case of the lever the length), and their sales prices.

2. Defining *process scenarios* for new possible production processes as well as for the existing process as a base line scenario. A process scenario has to cover information about the output rate of the system, the machine cost and its lifetime, the costs for tools and their lifetime, the switching costs which originates from setting-up the system for another product to be produced on the system, the various variable costs such as labor, energy and supplies, the raw material utilization, and the scrap rate.

3. Creating a *model* in which the behavior of the firm can be simulated depending on the diverse market and process scenarios. In that model general statements like costs for stock keeping and overdue parts, but also costs for overhead, number of workdays per year, shifts per day, and effective work hours per shift,

and material costs per unit are made. In this step also a simulation should be defined to generate random orders (within the boundaries defined in the market scenario) for the parts.

4. Running the *simulation* for every combination of market and process scenarios. The analysis of the results will then lead to the optimal process technology for this case study.

5. The *evaluation* of the simulation results lead to the most adequate manufacturing process for the problem.

Before starting, some general assumptions should be made:

- The price of one product is rather high for such a simple product. So, one can conclude that one length unit is not too small. Assume one length unit with 20 centimeters, so that L_A would be ten centimeters. The exact length is not important for the further calculation, it is just to give an idea that we are not in the fasteners markets and to provide some reasonable parameters for the process parameters.

- Due to the former statements it is quite possible that the firm competes in a niche market in which high market shares can be realized. Therefore the assumption is made that the firm has a market share of 70%.

- A small firm should manage to have low costs for overhead. So assume the total overhead costs with 15% of the manufacturing costs.

- Due to the simple product and the low overhead costs the material's portion of the manufacturing costs is likely to be very high and is therefore estimated to be 70% of the manufacturing costs.

- To prevent too much complexity, it is assumed that the levers only vary in length. The width and thickness are constant over all scenarios.

- There is a chance that the firm can sell 700,000 parts next year compared to 600,000 this year. That corresponds to an increase of $16\frac{2}{3}\%$. This enhancement can either base on growth of the market or on growth of the firms market share, or on both.

In the next three subsections the first three steps are described in detail. For the results of the simulation, see Section 3.3.

3.2.1 Market Scenarios

As described in Section 3.1, three possible states may occur next year, see Figure 3-5. These scenarios are named *Status Quo* for the most likely case in which the products

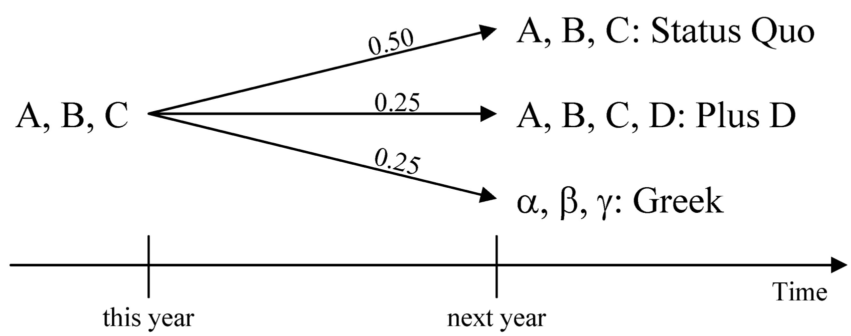

Figure 3-5: Three possible next year's state and their occurrence probability

are the same as this year, *Plus D* for the situation in which a fourth lever D is added to the three existing levers, and *Greek* for the event when the entire product line is replaced by a new one whose parts are identified by Greek letters. These three scenarios indicate different levels of complexity and uncertainty for the firm. They are ordered in increasing order of technical and managerial challenge.

Status Quo

There is a 50% chance that scenario *Status Quo*, which is the easiest of the three cases, comes true. That means that uncertainty is relatively low. No new products have to be introduced and also the projected sales volumes should be managed without major difficulties. It is assumed that there are no shifts of the market forces in this scenario.

So all the increases in sales are due to market growth only. In Table 3.2 the parts, their lengths, prices, sales volumes, and the increases in sales volumes compared to this year are listed.

Part	Length	Price	Volume	Increase
Lever A	0.500	$ 1.–	210,000	5.00%
Lever B	0.750	$ 1.50	375,000	25.00%
Lever C	1.000	$ 2.–	115,000	15.00%
Total			700,000	16.67%

Table 3.2: Products in scenario *Status Quo*

Plus D

The second scenario with a 25% occurence probability is *Plus D*. Here a new part, lever D, is introduced to enlarge the product familiy. The total market growth will be the same as in *Status Quo*. If the firm has a market share of 70% this year (as assumed above), the total market volume will be 1,000,000 pieces next year. Due to better fulfillment of the customers needs (introduction of part D) an increase in market share of 5% for the firm is assumed. That means that the firm can sell 750,000 parts next year. Lever D lies between levers B and C, so the firm has to accept that the new product cannibalizes its two neighbour parts. Therefore, for lever A the same increase rate is assumed as in *Status Quo*, but parts B and C will grow less than in the other scenario, see Table 3.3. The expected volume for lever D is calculated as

Part	Length	Price	Volume	Increase
Lever A	0.500	$ 1.–	210,000	5.00%
Lever B	0.750	$ 1.50	345,000	15.00%
Lever C	1.000	$ 2.–	108,000	8.00%
Lever D	0.875	$ 1.75	87,000	-
Total			750,000	25.70%

Table 3.3: Products in scenario *Plus D*

the residual difference to the total sales volume.

Greek

The last possible scenario is *Greek*. Its likelihood of occurence is also 25%. It is the most complex one out of our three cases. Not only is an entirely new product line developed to replace the present one, but also the demand volumes are subject to high uncertainty. The annual quantity of sales will fluctuate uniformly between 50,000 and 500,000 pieces per product. The prices for α, β and γ are assumed in relation to their lengths compared to this year's values. For details see Table 3.4.

Part	Length	Price	Volume
Lever α	0.400	\$ 0.90	50,000 – 500,000
Lever β	0.800	\$ 1.60	50,000 – 500,000
Lever γ	1.200	\$ 2.40	50,000 – 500,000
Total			150,000 – 1,500,000

Table 3.4: Products in scenario *Greek*

3.2.2 Process Scenarios

In this subsection six possible process scenarios are described. They are named *Progress*[1] *dedicated tool*, *Progress adjustable tool*, *Laser beam*, *Punching*, *Milling*, and *Infeed*. The scenarios distinguish themselves basically by the following parameters: (1) the output rate r_{Output} stands for the capacity per unit time and is measured in parts per minute, (2) the machine costs C_M in U.S. \$ are the initial costs for the acquisition of the machine, (3) the machine's lifetime T_{LM} in years is needed for the depreciation of the machine, (4) the tool's lifetime T_{LT} measured in the quantity of parts that can be produced with one tool before it must be replaced is also needed for the depreciation rate, (5) the switching time T_S in hours is needed to set up the machine for another product, (6) the variable costs C_{v_H} include wages, assumed with \$ 20 per hour, and costs for energy and other supplies, (7) the raw material utilization r_{Mat} indicates if the process requires material that cannot be used afterward (waste material), e.g. for gripping areas, (8) the scrap rate r_{Scrap} defines how many of the

[1] In analogy to 'progressive die' which stands for a tool used in a follow-on process

produced parts must be thrown away because they do not meet quality requirements, (9) the costs for the common tool C_{Tc}, measured in U.S. \$, can be depreciated over all products because the common tools are used for the production of all parts, and (10) the costs for the dedicated tools C_{Td} for each lever, also given in U.S. \$, can only be amortized by producing the adequate part. For details of these scenarios see the next paragraphs which are titled with the scenarios names.

Progess Dedicated Tool

This scenario describes the current manufacturing process in which a dedicated tool is used for each part. In a two step progressive process, first the holes are punched, and then in the second step the contour of the lever is cut. See Figure 3-6 for the tool. The raw material is a metal band. Even though, in this process some material from

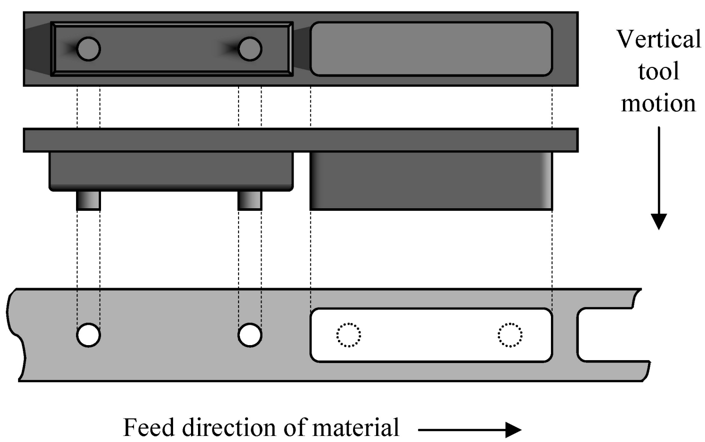

Figure 3-6: The tool for *Progress dedicated tool* and the metal band

the metal band is unused, the material utilization coefficient of this process scenario is set as 100% and acts as reference for the other process scenarios. The tool can be exchanged as one whole block and so the switching time is rather low. The scrap rate must be very low due to the dedicated tool, so it is set to zero. The tool costs are assumed with \$ 150,000 for the smallest part and then increase at a diminishing rate with the length of the lever. A reference for the output rate of 50 parts per minute can be found in Section 2.5. For other assumptions of this process scenario see Table 3.5.

Process		Tool costs	
Capacity r_{Output}:	50	Common tool C_{Tc}:	-
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	150,000
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	200,000
Tool lifetime T_{LT}:	1,000,000	Lever C C_{Td_C}:	250,000
Switching time T_S:	0.25	Lever D C_{Td_D}:	225,000
Variable costs C_{v_H}:	20	Lever α C_{Td_α}:	150,000
Material utilization r_{Mat}:	100%	Lever β C_{Td_β}:	225,000
Scrap r_{Scrap}:	0%	Lever γ C_{Td_γ}:	275,000

Table 3.5: Process parameters for *Progress dedicated tool*

Progress Adjustable Tool

Here a first step towards *'modular tooling'* is made. That means that parts of the tool are used by all, or at least several, products, and other parts of the tool can be dedicated to the product to manufacture. As shown in Figure 3-7 the end parts and the mid part of the tool are separated. As the end part tools can be used with every

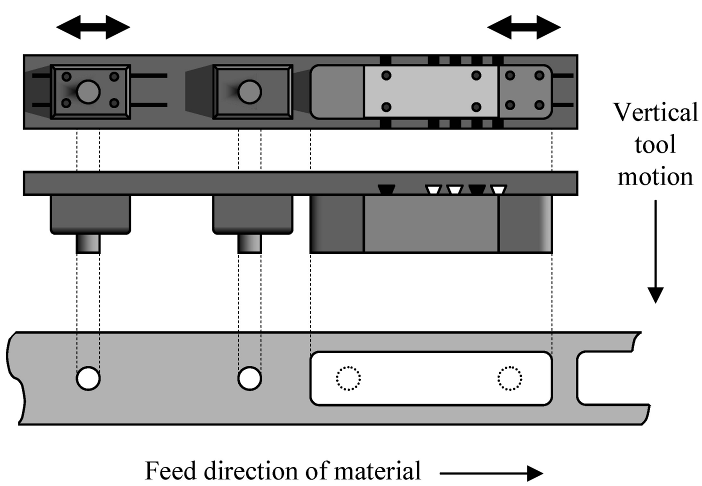

Figure 3-7: The tool for *Progress adjustable tool*

lever, the mid part is changed to match the needed length. While changing the tool, the mid tool of the precedent product is removed, the end part tools are adjusted to the right distance, and finally the mid tool for the new product is inserted into the press. For this more complicated operation, compared to *Progress dedicated tool*, the switching time for this scenario is doubled, see Table 3.6. The scrap rate is set to

Process		Tool costs	
Capacity r_{Output}:	50	Common tool C_{Tc}:	100,000
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	75,000
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	125,000
Tool lifetime T_{LT}:[2]	1,000,000	Lever C C_{Td_C}:	175,000
Switching time T_S:	0.5	Lever D C_{Td_D}:	150,000
Variable costs C_{v_H}:	20	Lever α C_{Td_α}:	75,000
Material utilization r_{Mat}:	100%	Lever β C_{Td_β}:	150,000
Scrap r_{Scrap}:	1%	Lever γ C_{Td_γ}:	200,000

Table 3.6: Process parameters for *Progress adjustable tool*

1% due to the fact that the probability of failure in the process is increasing with the degrees of freedom which are embedded in the tool. The manufacturing process itself is the same as in *Progress dedicated tool*.

Laser Beam

In this process, the levers are produced using a laser beam cutting machine. The raw material is sheet, therefore the material utilization is reduced to 90% because of the areas needed to hold the sheet. The capacity here is very low, but therefore costs for tools drop out. The amount of money set at 'common tool' is used for the maintenance of the laser device. Because maintenance is in made in advance to the use of the machine, bundle these costs togehter with variable costs would give a distorted image. Other assumptions for this process are shown in Table 3.7. The variable costs are high because the efficiency factor of today's laser is still low, so energy costs are very high. A side note: Water jet cutting would be another possible technology to manufacture the lever. According to [Rag03] laser beam cutting is more economic than water jet cutting as long as the metal sheet is thinner than 4 mm for aluminum and 8 mm for steel, respectively. Thus, in our lever problem water jet cutting would be worse than laser beam cutting in all scenarios and, hence, is no longer considered.

[2] Individual for every part of the tool, i.e., the common part of the tool must be replaced earlier than the dedicate ones.

Process		Tool costs	
Capacity r_{Output}:	4	Common tool C_{Tc}:	10,000
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	-
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	-
Tool lifetime T_{LT}:	1,000,000	Lever C C_{Td_C}:	-
Switching time T_S:	0	Lever D C_{Td_D}:	-
Variable costs C_{v_H}:	50	Lever α C_{Td_α}:	-
Material utilization r_{Mat}:	90%	Lever β C_{Td_β}:	-
Scrap r_{Scrap}:	5%	Lever γ C_{Td_γ}:	-

Table 3.7: Process parameters for *Laser beam*

Punching

The *Punching* process is quite similar to the *Laser beam* scenario. Raw material is sheet too, but more area is needed for gripping due to the circumstance that the sheet has to be moved relatively to the punching apparatus, while in *Laser beam* the head of the laser moves relatively to the sheet. The better process control is assumed to be better than in laser beam cutting, the scrap rate is lower than in the scenario above.

Process		Tool costs	
Capacity r_{Output}:	10	Common tool C_{Tc}:	20,000
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	-
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	-
Tool lifetime T_{LT}:	1,000,000	Lever C C_{Td_C}:	-
Switching time T_S:	0	Lever D C_{Td_D}:	-
Variable costs C_{v_H}:	30	Lever α C_{Td_α}:	-
Material utilization r_{Mat}:	85%	Lever β C_{Td_β}:	-
Scrap r_{Scrap}:	2%	Lever γ C_{Td_γ}:	-

Table 3.8: Process parameters for *Punching*

Milling

As one can imagine *Milling* is the slowest of all process scenarios. But therefore the variable costs are low (needs less energy than *Laser beam* and only few auxiliary materials), see Table 3.9. The 100% material utilization seems to be high for a milling process. For sure, in reality it is not 100%. As mentioned, we do not measure the

Process		Tool costs	
Capacity r_{Output}:	1	Common tool C_{Tc}:	25,000
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	-
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	-
Tool lifetime T_{LT}:	1,000,000	Lever C C_{Td_C}:	-
Switching time T_S:	0	Lever D C_{Td_D}:	-
Variable costs C_{v_H}:	30	Lever α C_{Td_α}:	-
Material utilization r_{Mat}:	100%	Lever β C_{Td_β}:	-
Scrap r_{Scrap}:	2%	Lever γ C_{Td_γ}:	-

Table 3.9: Process parameters for *Milling*

absolute material utilization, but the relative one compared to the *progess dedicated tool*.

Infeed

The last process scenario, *Infeed*, brings a new paradigm. The basic process is, as in the first and second scenario, stamping. Now, not the tools are changed to adapt the process to the parts, but the feeding of raw material is dependent on the product. As shown in Figure 3-8 the tool makes the front part of one lever in the same production cycle as the rear portion of the preceding component. To adjust the process to the

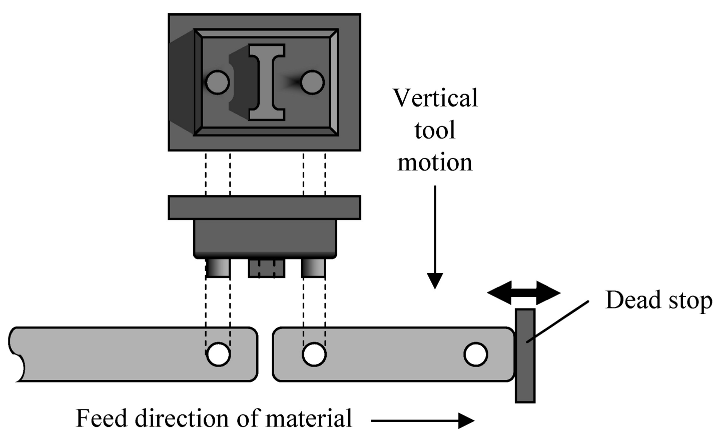

Figure 3-8: The tool for *Infeed*

product, a dead-stop is needed to control the infeed of the band material. Thus, flexibility is embedded in the process parameters, rather than in the tooling itself. It is necessary that the raw material has already the correct width, because only the end parts of the levers will be processed. The process parameters are listed in Table 3.10. Higher costs for the feeding control system and the dead end mechanism can be seen

Process		Tool costs	
Capacity r_{Output}:	30	Common tool C_{Tc}:	150,000
Machine costs C_M:	5,000,000	Lever A C_{Td_A}:	-
Machine lifetime T_{LM}:	10	Lever B C_{Td_B}:	-
Tool lifetime T_{LT}:	1,000,000	Lever C C_{Td_C}:	-
Switching time T_S:	0.05	Lever D C_{Td_D}:	-
Variable costs C_{v_H}:	20	Lever α C_{Td_α}:	-
Material utilization r_{Mat}:	100%	Lever β C_{Td_β}:	-
Scrap r_{Scrap}:	1%	Lever γ C_{Td_γ}:	-

Table 3.10: Process parameters for *Infeed*

as packed in the costs for the common tool as well as in the higher manufacturing costs per part due to the lower output rate, compared to *Progress dedicated tool* and *Progress adjustable tool*. *Infeed* is a special purpose process, where flexibility is embedded in one specific dimension (length), at the expense of other dimensions.

3.2.3 Model

In this subsection the third step of the approach is discussed. First, all input parameters are described. Second, the necessary calculations are derived. These calculations are programmed in Microsoft Excel using Microsoft Visual Basic. The program code written for this simulation is reproduced in Appendix D.

Input Parameters

Here, all input parameters that are neither part of a market nor of a process scenario are explained. Most of them had to be assumed with synthetic data. Therefore a sensitivity analysis (see Section 3.3.2) was made to show the robustness of the solutions.

Workdays One Year is assumed to have 250 Workdays.

Shifts The determination of the number of shifts a firm runs for a process scenario is based on the machine utilization rate. Whenever possible the enterprise runs at one shift. But if the demand cannot be satisfied, that means machine utilization is over 100%, a second shift and if necessary a third shift is added. Table 3.11 shows the number of shifts for each market and process scenario and machine utilization ratio (MUR) with the chosen number of shifts. A special case in every market scenario is

	Status Quo		Plus D		Greek	
	Shifts	MUR	Shifts	MUR	Shifts	MUR
Progressive dedicated tool	1	13.39%	1	14.39%	1	15.15%
Progressive adjust. tool	1	13.39%	1	14.39%	1	15.15%
Laser beam	2	83.70%	2	89.96%	2	94.66%
Punching	1	66.90%	1	71.97%	1	75.73%
Milling	3	100.00%	3	100.00%	3	100.00%
Infeed	1	22.32%	1	23.99%	1	24.24%

Table 3.11: Number of shifts and machine utilization ratio

Milling. Even though in this scenario the firm has to run three shifts, its capacity is still not high enough to fulfill the demand. The break even in capacity would be at eight shifts per day. So a second (and a third) machine should be added. But therefore the manufacturing costs would increase and the firm would not improve its performance.

Work hours A single shift is assumed to have seven effective hours.

Simulation of Demand Except in the case of market scenario *Greek*, in which the demand will fluctuate uniformly between a lower and an upper bound, the daily demand is assumed to be normally distributed with a mean value which is equal to one day's part of the annual demand[3]. The standard deviation for this normal distribution is set to 200 parts (per day).

In absence of a high fidelity simulation tool, a mean-normal-distribution simulator was programmed using only a random number generator. This random number gen-

[3]Even though GBM was introduced above, the demand now is simulated with a 'static' mean normal distribution to prevent too much complexity in the model.

erator choses a number between a lower and an upper bound. Now, to get a normal distribution, the lower and the upper bound themselves are picked as a randomly chosen numbers in the range of

$$\text{lower bound} \in [\text{mean value} - 2.667 \cdot \text{standard deviation} \ , \ \text{mean value}]$$
$$\text{upper bound} \in [\text{mean value} \ , \ \text{mean value} + 2.667 \cdot \text{standard deviation}]$$

The stretch factor 2.667 has been determined by adjusting it so that the mean value and the standard deviation of the result are equal to those two parameters (mean and standard deviation) serving as input variables. Using that self-made normal distribution simulator, the outcome is not correctly normal distributed. The result looks more like a triangular distribution than a normal distribution (see Figure 3-9). But the influence on the results of the final calculation is minor.

So, in cases of the market scenarios *Status Quo* and *Plus D*, the daily demand is simulated using the algorithm described above. As an example of the results, Table 3.12 and Figure 3-9 show the simulated values for the case of *Status Quo* and *Infeed*. The daily demand for each lever will be in the range shown in Table 3.12 (result of 100 simulation runs). In Figure 3-9 the distribution of lever A demands according

	Mean	Min	Max
Lever A	839	308	1369
Lever B	1503	970	2030
Lever C	459	0	990

Table 3.12: Example of range of daily demand

to the numbers in Table 3.12 is represented. It can be seen that a daily demand of around 830 pieces is the most probable case. Of the 250,000 simulated daily demands for lever A, 73 times, and hereby the most of all, an amount of 853 units has been ‘ordered’.

Overhead As mentioned above, costs for overhead should be rather low in a small firm. Therefore these expenses are assumed to be $r_{Overhead} = 15\%$ on top of the

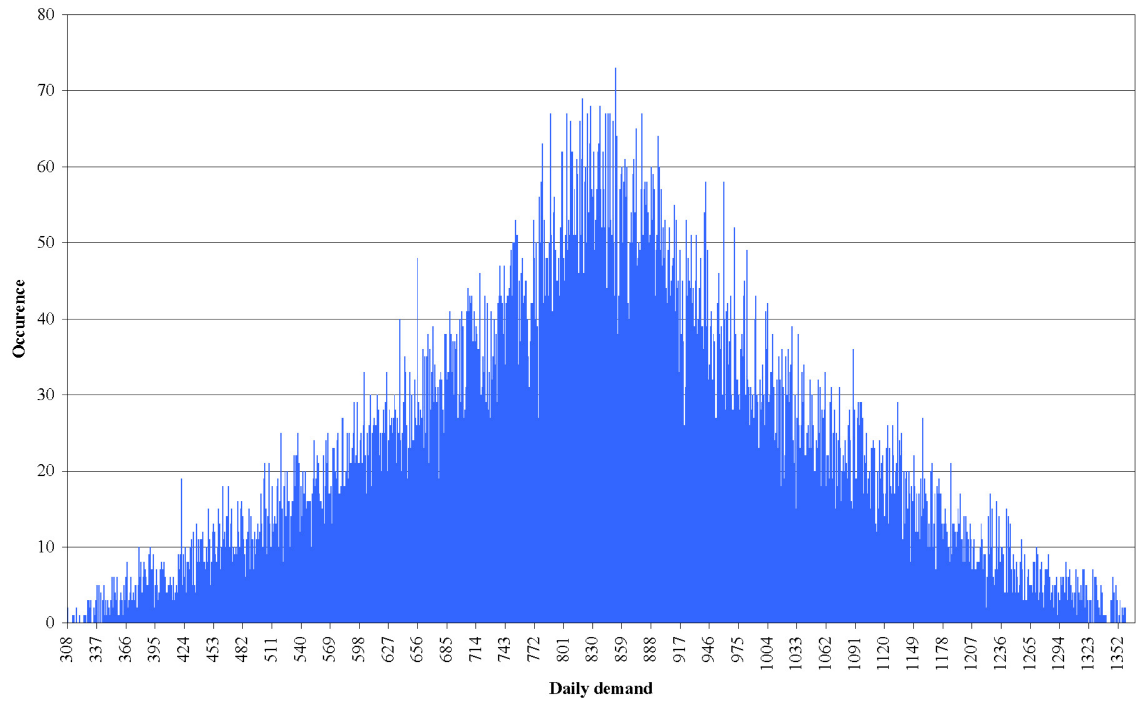

Figure 3-9: Daily demand of lever A in *Status Quo* and *Infeed* (100 simulation runs)

manufacturing costs. The same overhead rate is applied to all processes.

Material unit price One unit of raw material is defined to cost U.S. $ 0.95. So in accordance to the problem definition in Section 3.1 and the general assumptions in Section 3.2 the material is about 70% of manufacturing costs (which, for better comparison between the scenarios, does not include the switching costs for this estimation).

Stock keeping Parts that are produced but cannot be sold in a specific period are stored. Costs for storing are assumed to be $r_{Stock} = 25\%$ of the manufacturing costs for one year, see [Sei00, p. 52]. So the daily costs for storing one part are 25% of the up-to-date average manufacturing costs divided by the number or workdays per year. Because the average manufacturing costs vary from day to day due to different batch sizes, not all the parts on stock are charged with the same penalty for stock keeping.

Overdue parts Assume that the firm has a 24-hour delivery policy. So whenever possible, ordered products must be delivered the next day. Thus, parts are overdue if the demand cannot be satisfied in one period. If so, the parts must be produced in the next period with free capacity. It is assumed that the parts can be sold later, but due to the customers' irritation a rebate of $r_{Overdue} = 80\%$ of the original sale price has to be made. This rebate is calculated as cost in the period in which a part becomes overdue, but therefore, in the calculation, the part can be sold later at its original price.

Calculation

All variables used in the following equations are either derived here or have been defined in one of the sections above.

Production time per part Given the output rate (in parts per minute) in a process scenario, the production time per part (in hours) can be calculated as

$$T_{P_P} = \frac{1}{60 \cdot r_{Output}} \tag{3.2}$$

Capacity per day With the result of Equation 3.2 the production capacity per day is computed as

$$CAP_d = \frac{n_S \cdot n_H}{T_{P_P}} \tag{3.3}$$

The switching time in this model has no influence on the capacity. If implementing this specification, the difficulty of programming the model would leap to a higher level due to the fact that the capacity would have to be adjusted every day, and, thus, could not be used as a general input parameter. In addition, the results show that in process scenarios with a long switching time capacity is not a problem and in scenarios where capacity becomes crucial the switching time is low or even zero.

Machine costs per hour The investment and lifetime of the machine are given in the process scenario. So the machine costs per hour are

$$C_{M_H} = \frac{C_M}{T_{LM} \cdot n_D \cdot n_S \cdot n_H} \tag{3.4}$$

Switching costs per switching Assume that the machine is used also for the production of other parts, but the levers have priority. So with the beginning of every day, the machine first must be set up for the lever to be produced. Switching costs therefore are added to every production batch. The switching costs per switching can be calculated with the result of Equation 3.4 as

$$C_S = T_S \cdot (C_{v_H} + C_{M_H}) \tag{3.5}$$

Machine costs per part The Machine costs per part are the product of the production time and the machine costs per hour.

$$C_{M_P} = T_{P_P} \cdot C_{M_H} \tag{3.6}$$

Variable costs per part Given the hourly variable costs defined in the process scenario, the variable costs per part are

$$C_{v_P} = T_{P_P} \cdot C_{v_H} \tag{3.7}$$

Time dependent costs per part These costs are only an auxiliary number needed in further equations. C_{PT} are dependent on the production time per part and are defined as

$$C_{PT_P} = C_{M_P} + C_{v_P} \tag{3.8}$$

Costs common tool per part The parts' costs for the common tool are equal to

$$C_{Tc_P} = \frac{C_{Tc}}{T_{LT}} \tag{3.9}$$

It is important to notice that in process scenarios in which both common and dedicated tools are in use, the common tool has to be replaced earlier (in time) than the dedicated one due to the more frequent use.

Costs dedicated tool per part Analogous to Equation 3.9 the parts costs for the dedicated tool are calculated as

$$C_{Td_P} = \frac{C_{Td}}{T_{LT}} \tag{3.10}$$

Material costs per part For the computation of the parts' material price the raw material utilization has to be kept in mind

$$C_{Mat_P} = \frac{C_{Mat_U} \cdot L_P}{r_{Mat}} \tag{3.11}$$

Quantity dependent costs per part In contrast to Equation 3.8 the quantity dependent costs are independent of any time factor and are defined as

$$C_{PQ_P} = C_{Tc_P} + C_{Td_P} + C_{Mat_P} \tag{3.12}$$

Demand, Production, Sale, Stock and Overdue Figure 3-10 shows the main flow of the calculation. The equations are provided in the next few paragraphs, but, for better understanding, the process is already discussed here briefly. Demand is

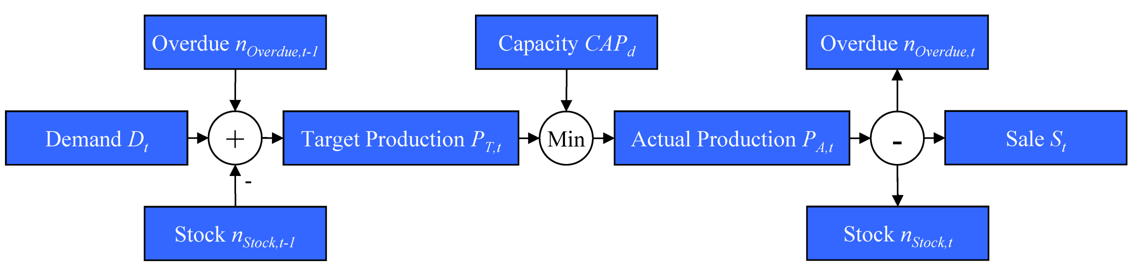

Figure 3-10: Main flow of calculation

given by the simulation tool. For determining the target production lot size, overdue parts from the last period are added and parts in stock from the last period subtracted. The available capacity bounds the actual lot size. If the actual production volume plus stock from last period is less then demand, parts become overdue. If the actual production is higher than demand plus the amount of overdue parts from the last period, parts go to stock. The firm can sale either as many parts as are demanded in the current period plus those which are backlogged from the last period, or as many as it produced in the current period plus those which are available on stock from the last period.

Target production The target production batch is either zero (when the actual demand is smaller than the disposal amount of pieces in stock) or the actual demand corrected by the number of stock and overdue parts

$$P_{T,t} = \max\left(0\ ,\ D_t - n_{Stock,t-1} + n_{Overdue,t-1}\right) \tag{3.13}$$

Scheduling Since in this model there is only one machine, and the product is produced in only one step and only on that particular machine, scheduling is not the core problem of this simulation. Nevertheless, scheduling can become interesting, particularly in the case when the demand reaches production capacity. To avoid stock keeping, the machine will be set up for every product once a day. So the question for scheduling is in which order the parts should be produced, or, if necessary, which parts should be made overdue. To answer this question the sales margin of the products are compared[4]. The product with the highest margin will be produced first, the product with the lowest margin is produced last. This makes sense as soon as not all demanded products can be produced in the same period as they are ordered. So the firm can maximize its profits due to minimizing the costs of overdue parts. One product's margin is calculated as the difference between its sale price and its manufacturing costs in the previous period. The margins are then sorted using the *Bubble Sort* algorithm as described in [Rag03, p. 198].

Actual production If planning with unlimited capacity, the actual production would be the same than target production. But following the last paragraph, that supposition is not true in this model. Hence, the target production must be compared

[4]Comparing the contribution margins would be another, better, possibility. But that data would require further calculations and, thus, decelerate the simulation.

with the remaining capacity of the production period.

$$P_{A,t} = \min\left(P_{T,t}\ ,\ CAP_d - \sum_{A}^{\gamma} P_{A,t}\right) \tag{3.14}$$

The indexes A and γ below and above the sum symbol stand for summing over all products. In Equation 3.14 the remaining capacity is calculated as the difference between the total capacity per day and the already spent capacity volume for producing other than the actual part that day.

Switching costs per part The switching costs per part are dependent on the production batch size. So they can be calculated as

$$C_{S_P,t} = \frac{C_S}{P_{A,t}} \tag{3.15}$$

Manufacturing costs per part In the manufacturing costs also the costs for overhead and scrap are included in the way that their rates are multiplied by the manufacturing costs which consider of the time dependent costs, the quantity dependent costs, and the switching costs

$$C_{Man_P,t} = \frac{\left(C_{PT_P} + C_{PQ_P} + C_{S_P,t}\right) \cdot (1 + r_{Overhead})}{1 - r_{Scrap}} \tag{3.16}$$

Account tool In this position the residual, or current, value of the tool is recorded. The tools are depreciated with every production cycle. So the balance of the tool account can be used as a metric of the capital bound in the tool. If, due to product changes, the current tool has to be thrown away, the money of the tool account is lost. In the simulation the current values of the tools are calculated as

$$V_{Tc,t} = V_{Tc,t-1} - P_{A,t} \cdot C_{Tc_P} \tag{3.17}$$

$$V_{Td,t} = V_{Td,t-1} - P_{A,t} \cdot C_{Td_P} \tag{3.18}$$

Sales The firm can sell as many parts in one period as are either ordered and overdue or available, meaning that they are produced and on stock

$$S_t = \min\left(D_t + n_{Overdue,t-1}\ ,\ P_{A,t} + n_{Stock,t-1}\right) \tag{3.19}$$

Stock The inventory of the current period is defined as

$$n_{Stock,t} = n_{Stock,t-1} + P_{A,t} - S_t \tag{3.20}$$

Overdue Analogous to Equation 3.20 the number of overdue parts is calculated as

$$n_{Overdue,t} = n_{Overdue,t-1} + D_t - S_t \tag{3.21}$$

Manufacturing costs cumulated To get the cumulated manufacturing costs the manufacturing costs per part are multiplied with the production amount

$$C_{Man,t} = C_{Man_P,t} \cdot P_{A,t} \tag{3.22}$$

Stock costs The costs for stock keeping are proportional to the number of parts in stock and their time in storage. So parts in stock cost the firm money in every period. For this equation the up-to-date average manufacturing costs are needed. Then the costs for stock keeping are calculated as

$$C_{Stock,t} = \frac{n_{Stock,t} \cdot r_{Stock} \cdot C_{Man_P,Average}}{n_D} \tag{3.23}$$

Overdue costs As described above, parts that are overdue get charged with 80% of their sale price at the time they get delayed, i.e. the firm earns only 20% of the original sales price, the rest is used for customer care. So, in contrary to the paragraph above, in one period, only the 'new' overdue parts must be penalized. Therefore the costs for overdue parts can be calculated as

$$C_{Overdue,t} = \max\left[0\ ,\ (n_{Overdue,t} - n_{Overdue,t-1}) \cdot r_{Overdue} \cdot R_P\right] \tag{3.24}$$

Total costs The total costs are the sum of the three cost types above

$$C_{Tot,t} = C_{Man,t} + C_{Stock,t} + C_{Overdue,t} \tag{3.25}$$

Revenue Given the (constant) sales prices, the revenue can easily be calculated as

$$R_t = S_t \cdot R_P \tag{3.26}$$

Earnings The earnings then are defined as

$$E_t = R_t - C_{Tot,t} \tag{3.27}$$

All calculations above (equations 3.10 – 3.27) are made for every single product, e.g. lever A. But, certainly, also the earnings of all products in one period is of interest

$$E_{Tot,t} = \sum_{A}^{\gamma} E_t \tag{3.28}$$

Costs for shipping are neglected in this model, one can assume that the customer has to pay for it. Inspection costs are integrated in overhead costs.

Summary

Finally, some key parameters are calculated to summarize the results. These numbers then are also used and discussed in Section 3.3.1 below.

Total Earnings This parameter tells how big the profit (or loss) of the lever product group will be in the simulated year

$$E_{Tot} = \sum_{t=1}^{250} E_{Tot,t} = \sum_{t=1}^{250} \sum_{A}^{\gamma} R_t - \sum_{t=1}^{250} \sum_{A}^{\gamma} C_{Tot,t} \tag{3.29}$$

The goal for this parameter is to reach a value as high as possible.

Final value of tool account The higher the value of this number the more money is remaining in the tools and is therefore running the risk of being lost in the next period

$$V_{Fin} = V_{Tc,t}\big|_{t=250} + \sum_{A}^{\gamma} V_{Td,t}\big|_{t=250} \tag{3.30}$$

Therefore the final value of the tool account can be seen as a reciprocal measure of *product flexibility*. Thus, the objective for this number is to be as low as possible.

Machine utilization The machine utilization ratio indicates the time during which the machine is used with the lever family compared to the total available production time

$$r_{Machine} = \frac{T_{P_P}}{n_D \cdot n_S \cdot n_H} \cdot \sum_{t=1}^{250} \sum_{A}^{\gamma} P_{A,t} \tag{3.31}$$

As mentioned above, the machine will not only be used for manufacturing levers, therefore a high MUR stands for high opportunity costs. Consequently, the aim for this number is to be as low as possible as well.

3.3 Solution Concepts

Combining the three market scenarios with the six process scenarios, 18 different business cases can now be analyzed. The results of the calculations themselves are subject to uncertainty, because of the simulation procedure with randomly chosen numbers for the demand. To get an expected value for the results instead of coincidence numbers, every business case is simulated 100 times. These results then are subsumed to a mean, a minimum and a maximum value for the most important parameters. Since we have only predictions for the next year, only one year is simulated. It can be assumed that at the end of next year similar options are available. Therefore, a low residual value of the tools at the end of the simulated year gives the firm more freedom of action due to less bound capital.

In this section, first the results of the simulation are discussed. Then, in the second subsection, a sensitivity analysis provides information about the robustness of the found results. Finally, to close the 'case study', a recommendation on how to proceed is given to the firm's executive board.

3.3.1 Results

Here, the three parameters *Total earnings*, *Tool account*, and *Machine utilization* are compared and discussed for every business case. All other data from the simulation can be found on the CD, see Appendix H. For these three key numbers, the mean, the minimum and maximum value, and the standard deviation are given in a table. In addition, the mean values then are shown in a chart to better compare the scenarios. These charts are all set to the same scales so that the diagrams can be compared easily. Observing only the mean values in the diagrams and not other characteristics like their standard deviation or minimum and maximum values as well, is sufficient since the results differ clearly from each other, and, in addition, the range of the final numbers, compared to their absolute values is very small. So, the usefulness of additional information would be marginal.

To make it easier to compare the results, all six process scenarios are discussed together for every market scenario. The numbers in parentheses mean negative values.

Status Quo

As mentioned in the beginning of Chapter 3, market scenario *Status Quo* is the most likely case. Thus, its importance is greater than those of the other market scenarios. In Section 3.2.1 an annual demand of 700,000 units was predicted. The results of the simulation show an average demand of 700,259 parts with a standard deviation of 5,308 pieces per year. In Table 3.13 and in Figure 3-11 the results of *Status Quo* are shown.

For this market scenario, *Infeed* is the process with the highest earnings as well as for its relatively low bound capital in the tools at the end of the year. Regarding the earnings, *Infeed* is followed closely by *Progress dedicated tool*, and, already with some distance, *Progress adjustable tool*. The other three process scenarios will not result in

Process scenario	Earnings E_{Tot}			
	Mean	Min	Max	STD
Dedicated tool	151,656	147,674	157,199	1,918
Adjustable tool	56,292	52,788	61,330	1,709
Laser beam	(328,946)	(337,264)	(322,672)	2,743
Punching	(103,570)	(105,949)	(101,234)	959
Milling	(924,767)	(941,323)	(912,122)	5,383
Infeed	176,099	171,893	181,419	1,875
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	349,692	346,523	352,048	1,088
Adjustable tool	313,571	309,599	316,749	1,389
Laser beam	4,146	4,028	4,244	43
Punching	8,292	8,057	8,487	85
Milling	19,996	19,807	20,220	76
Infeed	62,189	60,427	63,654	638
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	13.338	13.111	13.640	0.101
Adjustable tool	13.338	13.111	13.640	0.101
Laser beam	83.363	81.943	85.250	0.632
Punching	66.691	65.554	68.200	0.506
Milling	100.000	100.000	100.000	0.000
Infeed	22.230	21.851	22.733	0.169

Table 3.13: Results of the simulation for *Status Quo*

positive net earnings.

Reasons for the existence of these two groups are mainly twofold. First, *Laser beam* and *Milling* are, due to their low capacity, charged with enormous overdue costs. The low capacity of those two processes can be seen clearly in Figure 3-11 if one follows the gray points which indicate the machine utilization ratio. Second, also for *Punching*, manufacturing costs per part for these three scenarios are at such a high level that they cannot lead to positive product profitability. The higher manufacturing costs of the three technologies can be explained with the higher variable costs in combination with the lower output rate, i.e., higher costs per hour must be distributed to share less parts per hour.

The cause for *Progress adjustable tool's* gap to *Progress dedicated tool* and *Infeed*

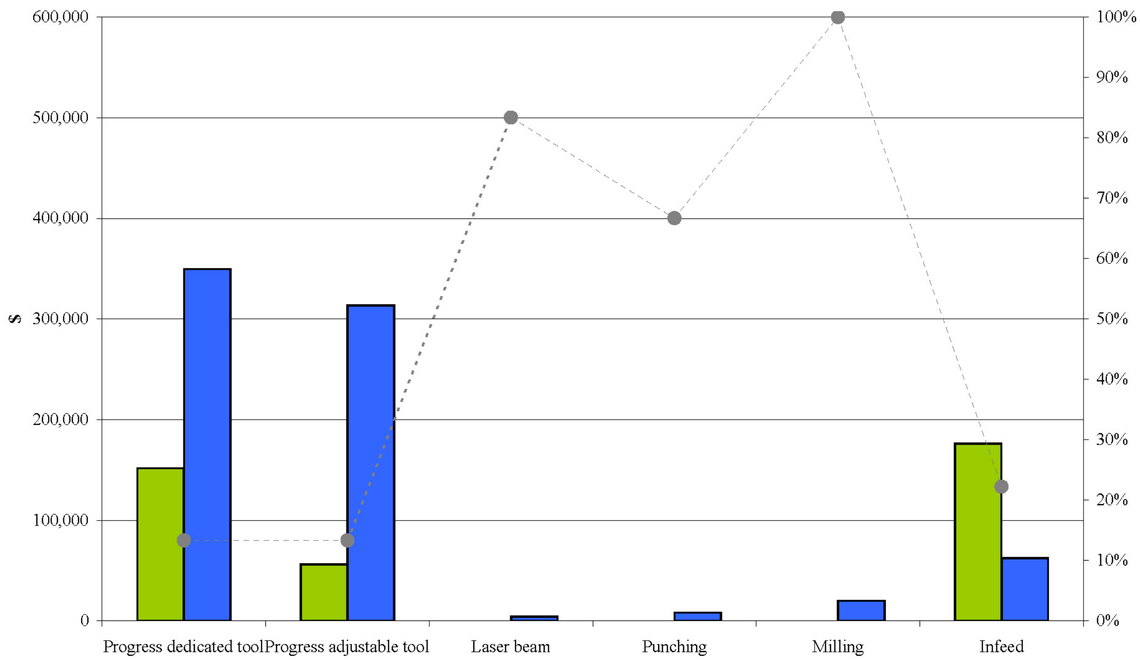

Figure 3-11: Results of the simulation for *Status Quo*

lies mainly in the switching time. Due to the doubled switching time compared to *Progress dedicated tool*, *Progress adjustable tool* makes a loss with the A-levers.

It has to be kept in mind, that only in the process scenario *Progress dedicated tool* the current tools can be reused, because it is the current manufacturing process. For all other settings new tools have to be acquired. Therefore the tool account's ranking for *Progress dedicated tool* has an advantage of \$ 115,000. But still with this head start, continuing with this year's technology is the worst case regarding the remaining value of the tools at the end of the simulated year. It may be surprising that *Milling* has a higher value on the tool account than *Punching*. The reason for this is, that while both process scenarios have about the same start values, *Milling* produces fewer parts than *Punching* and therefore its tool are less amortized.

Plus D

The assumed annual demand for market scenario *Plus D* is 750,000. The 'real' value as a result of the simulation is 751,155 levers for the whole year. This mean demand is distributed over the 600 runs[5] with a standard deviation of 6,182 parts. The demand increases about 7%, compared to *Status Quo*, so one would inherently agree that the earnings should be about 7% higher in this scenario too. But, as shown in Table 3.14 and in Figure 3-12 this is not the case.

	Earnings E_{Tot}			
Process scenario	Mean	Min	Max	STD
Dedicated tool	154,006	148,317	161,669	2,404
Adjustable tool	35,243	30,236	42,402	2,178
Laser beam	(351,511)	(361,060)	(343,818)	3,709
Punching	(103,671)	(106,173)	(100,962)	955
Milling	(979,027)	(997,165)	(962,182)	6,585
Infeed	195,362	189,854	202,795	2,410
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	562,695	558,733	565,899	1,330
Adjustable tool	450,829	445,791	454,668	1,654
Laser beam	3,567	3,466	3,713	50
Punching	7,133	6,932	7,415	99
Milling	19,821	19,627	20,035	80
Infeed	53,501	51,991	55,611	746
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	14.308	14.025	14.639	0.118
Adjustable tool	14.308	14.025	14.639	0.118
Laser beam	89.416	87.655	91.496	0.736
Punching	71.538	70.124	73.197	0.589
Milling	100.000	100.000	100.000	0.000
Infeed	23.846	23.375	24.399	0.196

Table 3.14: Results of the simulation for *Plus D*

The earnings of *Infeed* increase about 11% and *Progress dedicated tool* could at least step up about 1%. While *Infeed* apparently benefits from economies of scale, its direct competitor scenario struggles with high manufacturing costs, especially for the new lever D. The reason for that are the high tooling costs for this process. The other process scenarios remain static or are even worse, respectively. In case of the stagnating process, *Punching*, the low material utilization rate pushes manufacturing

[5] 100 runs for each of the six process scenarios

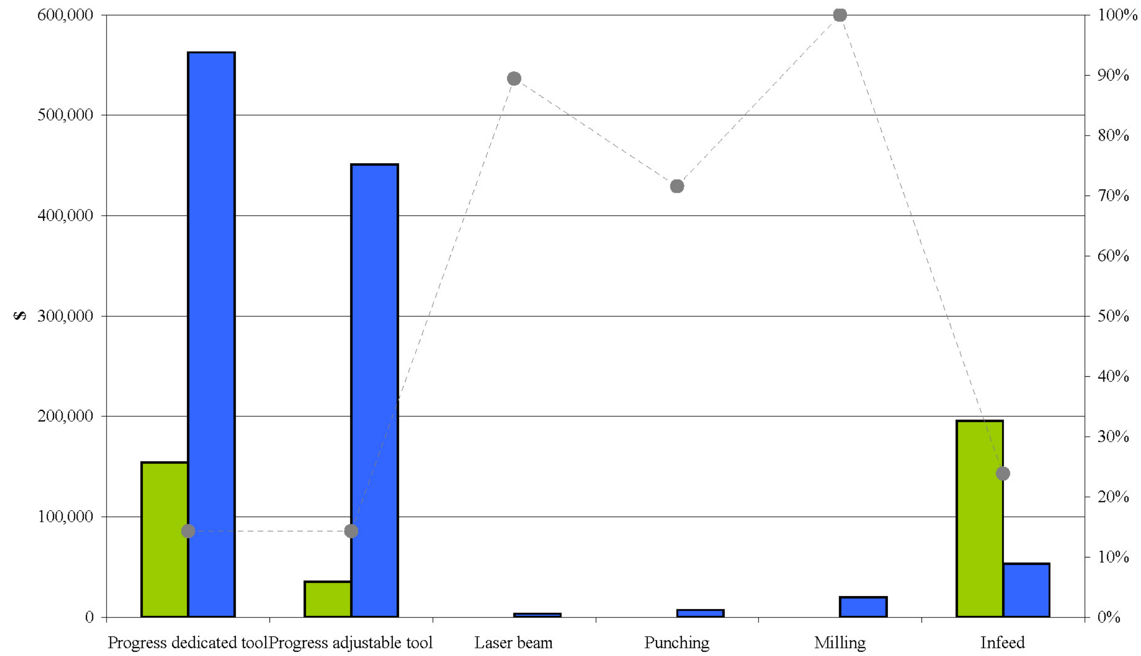

Figure 3-12: Results of the simulation for *Plus D*

costs to a level that is no more competitive. *Progress adjustable tool*, *Laser beam*, and *Milling* would be well advised to not produce lever D and, however, make more earnings with fewer parts.

An interesting aspect in this scenario are the extraordinary high values for the tool accounts in the two *Progess* technologies. They come from the circumstance that a new tool for lever D has to be manufactured. However, the quantities of the new lever are at a very low level, around 350 parts per day compared to 450 for lever C, 850 and 1,350 pieces for A and B, respectively. That means that the initial costs for the new tool, which are in between the tool costs of lever B and C, cannot be amortized fast enough and, thus, show up at the end of the year in an 'impressive' way. The other processes, on the other hand, gain from their multi usable tools.

Comparing the absolute results of *Plus D* gives a similar view as in the findings of *Status Quo*. *Infeed* leads the ranking list followed by *Progress dedicated tool* and *Progress adjustable tool*. The three slower processes, as in the previous concept, close their balance sheets with negative earnings. The reasons for that ranking order are mainly the same as before.

Greek

With an average annual demand of 824,490 levers, the sales data of *Greek* lie clearly above the other two market scenarios (18% and 10% opposite to *Status Quo* and *Plus D*, respectively). Thus, *Greek* is only limited comparably to the others. However, the main question of the 'lever problem' is not to compare different market scenarios with each other, but to determine the best production technology for possible market scenarios. Nevertheless, the results shown in Table 3.15 and Figure 3-13 will shortly be compared to the precedent market scenarios.

	Earnings E_{Tot}			
Process scenario	Mean	Min	Max	STD
Dedicated tool	258,007	241,616	271,892	6,474
Adjustable tool	156,484	141,344	169,135	5,889
Laser beam	(367,908)	(389,136)	(345,741)	10,100
Punching	(60,228)	(69,988)	(51,066)	4,214
Milling	(867,368)	(903,430)	(827,563)	17,490
Infeed	299,040	281,346	313,016	6,593
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	471,382	464,600	479,048	3,296
Adjustable tool	398,971	390,023	409,316	4,332
Laser beam	4,561	4,333	4,798	103
Punching	9,006	8,507	9,596	240
Milling	23,978	23,452	24,424	211
Infeed	67,529	63,803	71,970	1,796
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	15.705	15.013	16.283	0.289
Adjustable tool	15.705	15.013	16.283	0.289
Laser beam	97.456	93.506	99.961	1.438
Punching	78.513	75.066	81.414	1.444
Milling	100.000	100.000	100.000	0.000
Infeed	26.174	25.022	27.138	0.482

Table 3.15: Results of the simulation for *Greek*

All processes, except *Laser beam*, will realize a higher profit than in the other market settings. Due to the noticeable higher volumes, overdue costs for *Laser beam* nearly doubled, and consequently increase the loss of this process scenario. This

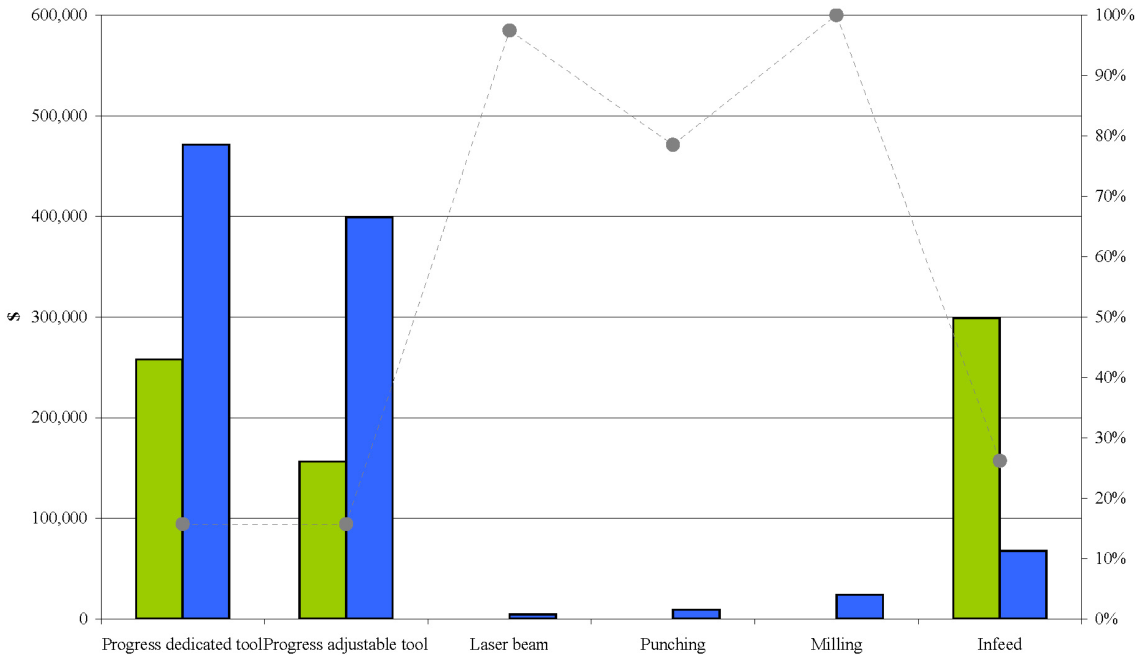

Figure 3-13: Results of the simulation for *Greek*

downside could be eliminated by adding a third shift; then the loss would only be around $ 112,000. Doing so could be justified by referencing to Section 3.2.3 where it says that shifts will be added if MUR reaches 100%, and *Laser beam* is with 97% very close to that mark. But otherwise, *Laser beam* in *Greek* then could no longer be compared with *Laser beam* in the other market scenarios.

Greek is the only market scenario in which all production processes have the same premises. Because the current levers are replaced by new products, no old tools can be reused in this scenario[6]. A 'greenfield' simulation, quasi. Therefore the blue bars in Figure 3-13, which picture the residual value of the tools, show the 'correct' situation of the inverse product flexibility of the different processes. But the ranking is still the same. *Laser beam* contains least value in its tools, succeeded by *Punching*, *Milling*, and *Infeed*. These four processes come off very well compared to *Progress adjustable tool* and *Progress dedicated tool* whose final results are five to ten times higher than those of the first group, in terms of residual tool value.

There is nothing new also with the results of the earnings. *Infeed* is still the most

[6]Only tools for *Progress dedicated tool* exist by now.

profitable process technology, followed closely by *Progress dedicated tool* and *Progress adjustable tool*. Negative outcomes are predicted for the other three processes.

3.3.2 Sensitivity Analysis

Although the results partly differ very much, the question is how robust these solutions are. A sensitivity analysis produces this information, e.g. see [LÖ0]. The sensitivity analysis is formulated with the input parameters that are used in the simulation of *Status Quo*. *Status Quo* was chosen because, first, it is the most likely market case. And second, its absolute results are closest together, i.e., varying the input parameters in this scenario will have the biggest influence on the results and their ranking. The sensitivity analysis is made for all input variables for all process scenarios in *Status Quo*. It is conducted 'ceteris paribus', which means that only a single parameter is changed at once while all other values remain fixed. Since we are mainly interested in a relative comparison of the processes, rather than absolute answers, this sensitivity analysis does not provide any information about the tendency and the amplitude of the result if an input parameter is changed. But, it shows the range in which an input parameter can be varied *without* changing the ranking of the results.

In this subsection the results of *Infeed* and *Progress dedicated tool* are discussed. This is because as soon as these two processes change places an other technology would be best for the firm, and therefore special attention should be paid to these two production settings. All other results of the sensitivity analysis are listed in Appendix E.

To determine the window of opportunity of an input parameter, e.g. the output rate of *Infeed*, the value of this variable is increased and decreased, respectively, as long as the ranking of both the earnings and the tool accounts remain the same. In Table 3.16 and in Figure 3-14 the results of this analysis for the winning technology *Infeed* are shown.

The table is read in the way that a parameter can be reduced from its actual value to its minimal value, and neither the ranking of the earnings nor of the tool accounts ranking change. But if the parameter is further decreased an other process will take the analyzed process' position in the ranking list. The analogous action is used for the maximum value. A hyphen '-' in the table means that changing a parameter in the indicated direction has no influence on the ranking list and can therefore be set to infinite. An asterisk '*' in the table is set to indicate boundaries at which the ranking of the *tool account* changes. Numbers without an asterisk set limits at which the ranking of the *earnings* changes.

The figure provides the same information as the table, but in addition, shows graphically the possible variation range of the input parameters in percent of the actual value. The actual value is the number written in the middle of bar. While green bars indicate a parameters 'elbowroom' without changing the earnings ranking list, blue bars represent margins, whose exceedance changes the ranking of the tool accounts. Bars that are open at the right end extend beyond the +300% scale in the chart.

While analyzing these results, one has to bear in mind, that there are positively correlated input parameters such as output rate (the higher the value the better the performance) and negatively correlated ones such as costs for tools (the higher the value the worse the performance).

Parameter	Min value	Actual value	Max value
Costs common tool C_{Tc}	75,440*	150,000	179,833
Output rate r_{Output}	25	30	-
Switching time T_S	-	0.05	0.14
Variable costs C_{v_H}	-	20	69
Raw material utilization r_{Mat}	96%	100%	-
Useful parts $(1 - r_{Scrap})$	96%	99%	-

Table 3.16: Range of input parameters for *Status Quo* and *Infeed* for steady ranking

As shown in Table 3.16, e.g., the current output rate of *Infeed* is 30 units per minute. This value can be reduced to 25, and *Infeed* is still the winning technology. But if *Infeed's* output rate is set to 24 or lower, the next process in the ranking, *Progress dedicated tool*, will be the leading process. Figure 3-14 indicates that the output rate may be reduced by approximately 17% from its original value. The

*Enforces change in ranking of tool account

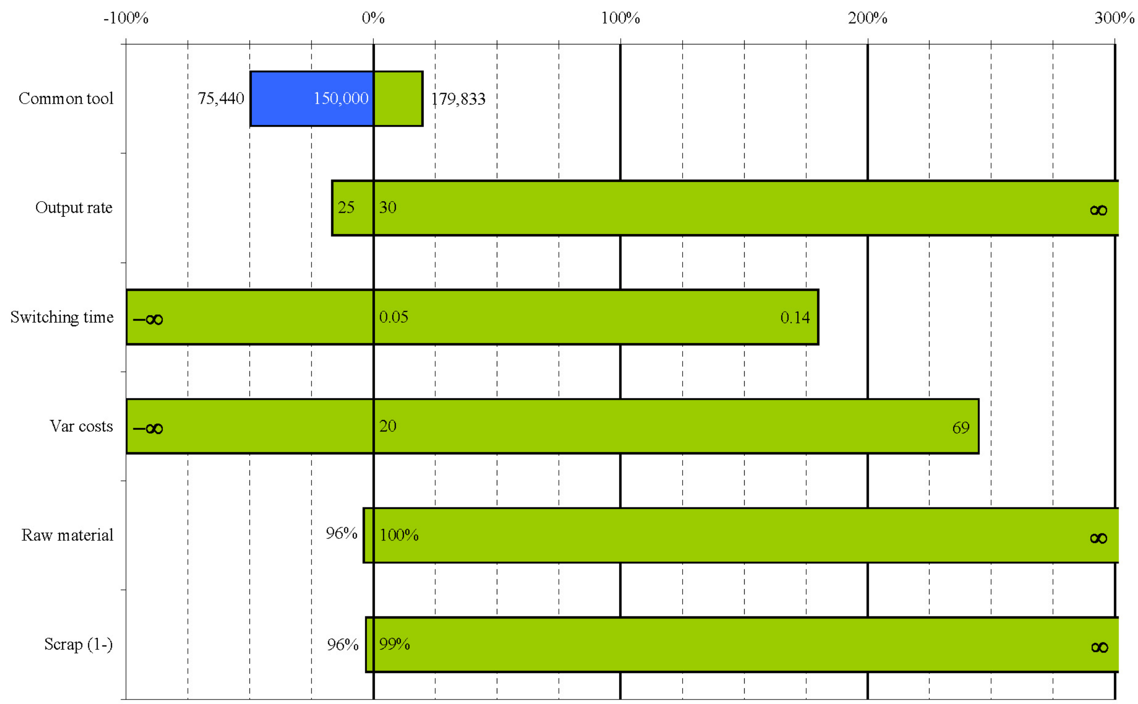

Figure 3-14: Range of input parameters for *Status Quo* and *Infeed* for steady ranking

switching time, as an other example, can be increase by about 180% from its actual value 0.06 hours to 0.14 hours, and then, at 0.15 hours *Progress dedicated tool* would yield better performance. As a last sample, if the costs for the common tool are reduced by around 50% to \$ 75,440 *Milling* and *Infeed* would change places in the ranking of the tool account because *Milling* is the next best process scenario to *Infeed*, see Figure 3-11. But if the common tool costs exceed \$ 179,833 which is roughly 20% above the actual value, *Progress dedicated tool* will beat *Infeed* in terms of earnings.

In Table 3.17 and Figure 3-15 the windows of opportunity for *Progress dedicated tool* are presented. It may be surprising that if the tool costs reach a particular value, higher than the actual value, the ranking list of the tool account will change. Since *Progress dedicated tool* comes in last for the residual value of the tools, see Figure 3-11, it seems illogical to advance in ranking while increasing costs. And this is, actually, a mistake in the proceeding in the sensitivity analysis. (But due to lack of time, the analysis cannot be redone). It is obvious, that with increasing costs of the tool, also the residual value in the tool increases. If the costs for a tool increase by ΔC_T, while tool lifetime T_{LT} and production volume P_A remain the same, the new

Parameter	Min value	Actual value	Max value
Costs tool A C_{Td_A}	48,371	150,000	282,191*
Costs tool B C_{Td_B}	144,406	200,000	272,312*
Costs tool C C_{Td_C}	63,394	250,000	492,721*
Output rate r_{Output}	24	50	70
Switching time T_S	0.15	0.25	0.61
Variable costs C_{v_H}	-	20	217
Raw material utilization r_{Mat}	85%	100%	-
Useful parts $(1 - r_{Scrap})$	90%	100%	-

Table 3.17: Range of input parameters for *Status Quo* and *Progress dedicated tool* for steady ranking

residual value of the tool can be calculated as

$$V_{new} = C_T + \Delta C_T - \frac{P_A \cdot (C_T + \Delta C_T)}{T_{LT}} \tag{3.32}$$

so the change in the tool account ΔV as the difference between the new V_{new} and the old value V_{old} can be expressed as

$$\Delta V = \Delta C_T - \frac{P_A \cdot \Delta C_T}{T_{LT}} \tag{3.33}$$

and is positive as long as P_A is smaller than T_{LT}, i.e. V_{new} is always higher than or equal (in the case of $P_A = T_{LT}$) V_{old}. If P_A is bigger than T_{LT}, a new tool has to be bought and therefore depreciation process begins anew. (In the, uncorrect, sensitivity analysis, only the higher depreciation was considered, but from the old (lower) start value C_T. But, this has only influence on the range of the tool costs and the ranking of the tool accounts, the other results are not affected by this mistake.)

Summarizing the data in Tables 3.16 and 3.17 it can be said that *Infeed* remains the winning technology as long as:

- the costs for the tool in *Infeed* do not exceed \$ 179,833,
- *Infeed's* output rate is not lower than 25 parts per minute,
- the switching time for *Infeed* is not more slowed down as to 8.4 minutes,

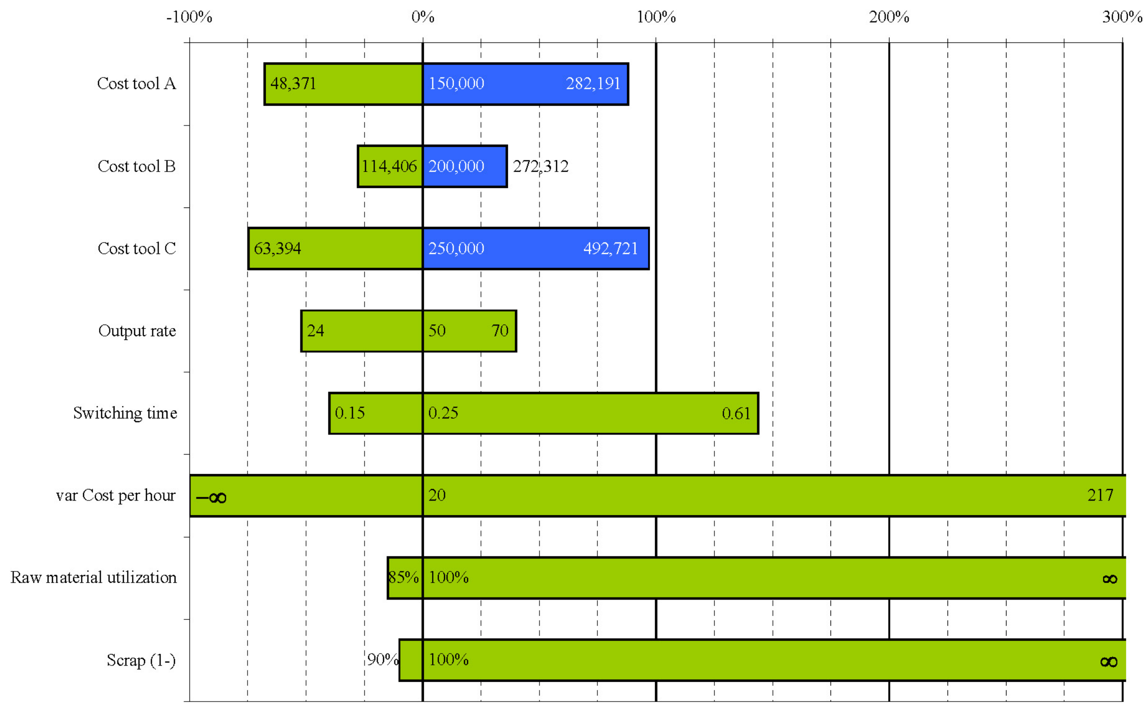

Figure 3-15: Range of input parameters for *Status Quo* and *Progress dedicated tool* for steady ranking

- the variable costs per hour do not exceed \$ 69,
- *Infeed's* material utilization is 96% or higher,
- the scrap rate of *Infeed* is not higher than 4%,
- the tool costs in *Progress dedicated tool* are not below \$ 48,371 for tool A, \$ 114,406 for tool B, and \$ 63,394 for tool C,
- the output rate of *Progress dedicated tool* does not exceed 70 parts per minute, or
- the current proccess' switching time is not speed up more than to 9 minutes.

It has to be kept in mind, that the sensitivity analysis is made 'ceteris paribus'. So, the listing above is an 'OR'-statement and not an 'AND'-conclusion. Nothing is said about the robustness of the solution while changing more than one parameter at a time. Nevertheless, the winning solution, *Infeed*, seems to be relatively stable. At least it is hardly reasonable to change several variables on a large-scale only in one process scenario and not adapting the other technologies.

3.3.3 Summary and Recommendation

To get a numerical answer to the question posed in Section 3.1, three market scenarios and six process scenarios are created. Every market scenario then is combined with every process scenario which result in 18 different business cases. Every business case is simulated one hundred times in order to obtain an expected value for the total earnings, the remaining value in the tools, and the machine utilization. The results are unambiguous. In all market scenarios, *Infeed* realizes the biggest profit of all process scenarios. The role of the 'eternal bridesmaid' belongs to *Progress dedicated tool* whose earnings are, even if only somewhat, lower than those of the winning technology. In the third place in all market settings, *Progress adjustable tool* has already a big shortfall. The other three process scenarios operate at a deficit in all market cases.

Not only is *Infeed* the winning process technology in all market scenarios, it is also the only process scenario which has a 'earnings-to-tool account' ratio that is greater than one. This ratio can also be expressed as an earnings-to-risk ratio.

The conclusion, and hereby the end of the case study 'the lever problem', is the recommendation to the firms management to replace the current production technology by *Infeed*. Since the new technology is also a stamping process, it should be possible to reuse the press. Anyhow, some adaptations, like better guidances, better feed control, and the dead-stop, are necessary.

3.4 The Lever in the Aerospace Industry

The lever problem as stated above could be a good example for a firm that is a supplier to the automotive industry. Since the title of this thesis is 'Flexibility in

Aerospace and Automotive Component Manufacturing Systems', something similar should be done for the aerospace industry. Therefore the lever problem is adjusted to explore a low volume, high uncertainty, and high parts value environment.

The same calculations as described in Section 3.2.3 are made again. Of course, some changes in the input parameters have to be made.

3.4.1 Scenarios and Input Parameters

Parameters that will change for the following calculation are described in this subsection. All other input parameters remain as in the lever problem for the automotive industry.

Status Quo The volumes are set to a hundredth of the original scenario, so the yearly demand is 7,000 parts. The sale prices therefore, are increased dramatically as shown in Table 3.18.

Part	Length	Price	Volume
Lever A	0.500	$ 15.–	2,100
Lever B	0.750	$ 22.50	3,750
Lever C	1.000	$ 30.–	1,150
Total			7,000

Table 3.18: Products in scenario *Status Quo*

Plus D In an analogous manner *Plus D* is altered, see Table 3.19 for the new input parameters. For the sales volumes the same thoughts as in Section 3.2.1 are valid.

Part	Length	Price	Volume
Lever A	0.500	$ 15.–	2,100
Lever B	0.750	$ 22.50	3,450
Lever C	1.000	$ 30.–	1,080
Lever D	0.875	$ 26.25	870
Total			7,500

Table 3.19: Products in scenario *Status Quo*

Greek In market scenario *Greek* the demand will fluctuate uniformly between zero and 5,000 pieces per product and year. The prices are set in proportion to the lengths of the levers, see Table 3.20

Part	Length	Price	Volume
Lever α	0.400	\$ 12.–	0 – 5,000
Lever β	0.800	\$ 24.–	0 – 5,000
Lever γ	1.200	\$ 36.–	0 – 5,000
Total			0 – 15,000

Table 3.20: Products in scenario *Greek*

Process Scenarios The process scenarios are the same as in the original lever problem.

Shifts Since in the new problem the demand is that low, all process scenarios can work with only one shift.

Simulation of Demand The standard deviation for the daily demand in market scenarios Status Quo and Plus D is set to 10 pieces per product (the average daily demand for all lever types is around 30 parts). This is about five times the STD of the automotive case with 200 pieces compared to an average daily demand of 2,800 parts. Herewith, the higher uncertainty in the aerospace industry is expressed.

3.4.2 Results

The results of the lever problem in the aerospace industry show, as expected, a completely different image. Here only the results of the market scenario *Status Quo* are discussed. The tables and charts of the results of all market settings can be found in Appendix F.

Figure 3-16 pictures the performances of the process scenarios in a low volume environment. No longer is *Infeed* the winning technology, but *Punching* takes the lead. With total earnings of \$ 162,817 this process earns about \$ 8,000 more than

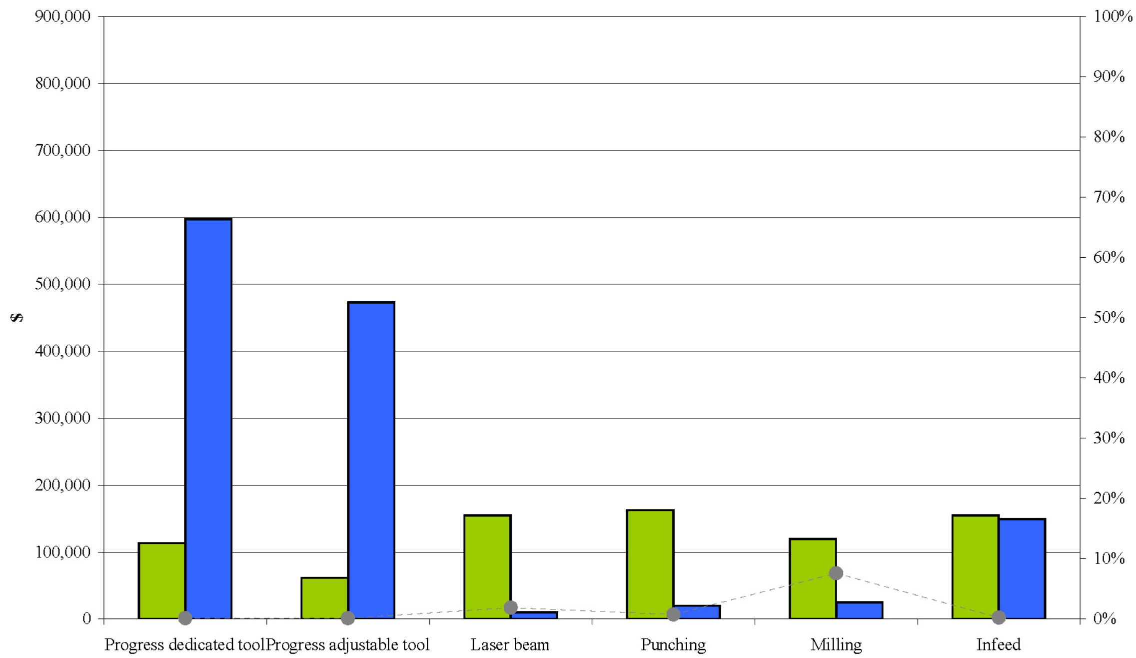

Figure 3-16: Results of the simulation for *Status Quo*

the second process, *Laser beam*, with a sum of $ 154,698 in average. *Laser beam* is closely followed by *Infeed* whose average earnings lie at $ 154,635. Although these three processes can be put in an order for compiling a ranking list, the distances are very short with only 5% between *Punching* and the other two technologies, and 0.05% between *Laser beam* and *Infeed*, respectively. A middle group can be built with *Milling*, $ 119,318, and *Progress dedicated tool*, $ 113,597. *Progress adjustable tool* has fallen behind with total earnings of $ 61,688, about half the value of the mid group and about a factor 2.5 to the top group. This is surprising, initially, since modular tooling is often presented as a flexible production strategy for low volume and high uncertainty, but in our case, the tool costs are too high to utilize this flexibility.

Two main drivers for this change can be determined. First, the tooling costs per part for the three follow-on processes are about ten times higher than the ones of *Laser beam*, *Punching*, and *Milling*. Second, the high switching times of *Progress dedicated tool* and *Progress adjustable tool* cause, due to the tiny batch sizes, switching costs per part are on the same order of magnitude as the parts sale prices and, thus, absorb the bulk of the products' margin.

Regarding the residual values of the tools, the ranking list looks the same as in the results discussed in Section 3.3.1. *Progress dedicated tool* has the least result with \$ 597,289 followed by *Progress adjustable tool* (\$ 473,122), and *Infeed* (\$ 149,059). *Laser beam* (\$ 9,937) has the least value on its tool account, at the second place is *Punching* with \$ 19,875 followed by *Milling* (\$ 24,843).

Machine utilization is low, even the highest value is still below 10%, this can be seen clearly in Figure 3-16.

A sensitivity analysis for the input parameters of this case would be very meaningful too, but has to be skipped for time reasons.

As conclusion for 'the lever in the aerospace industry' the recommendation for producing the levers by *Punching* or *Laser beam* has to be made. Not do these two process scenarios yield the most earnings, they also have an excellent 'earnings-to-tool account' ratio. Nevertheless, *Infeed* would still be a viable process, especially if the firm has already an applicable press with enough free capacity.

3.5 Summary

In this chapter, the case study 'the lever problem' is fleshed out. Facing the situation of uncertainty in terms of demand as well as in parts geometry, the CTO of a small firm searches for new process technologies to make his manufacturing facility more flexible. Three possible market scenarios are modeled to represent different levels of uncertainty. In *Status Quo* only the number of demanded parts is increased while the parts themselves remain the same. At the next higher level of uncertainty, *Plus D*, a new part is added to the existing product family. In scenario *Greek* the current products are completely replaced by a new part family and the demand fluctuates uniformly in a wide range.

Six different process scenarios are defined, all possible ways to produce the demanded parts. The five processes that are added to the actual one are all more flexible than the current one according to the meaning of product flexibility as defined in Section 2.2.1. They differ mainly in terms of output rate, costs for tools, and variable costs. Combining the three market and the six process scenarios 18 business cases emerge. Every business case is simulated to enable selection of the best process technology for each market scenario.

This procedure is done twice. First, for an environment which could be entitled as 'automotive industry'. High volumes require high output rates and therefore low variable costs. Referring to Figure 1-2 this would be case B. The process scenarios *Progress dedicated tool* and *Progress adjustable tool* describe manufacturing processes typically encountered in supplier companies for the automotive industry. Also in the simulation described in this chapter, these technologies perform very well.

The second time, the lever example is placed in the 'aerospace industry'. Low volumes require low investment, therefore higher variable costs are more readily accepted. This would be case A in Figure 1-2. Process technologies similar to *Laser beam*, *Punching*, or *Milling* are prevalent in that industrial sector. Herewith, the results found above are confirmed indirectly. The processes with a lower output rate, lower fixed costs and higher variable costs perform better than the ones that prevail in a high volume scenario.

In Section 1.1.1 the question was posed which technology will be best in case C of Figure 1-2. *Infeed* could be a possible answer to that matter. *Infeed* is the winning process scenario in the automotive situation and comes in third in the aerospace settings, with only a tiny gap. It can be concluded, that a technology that performs best in the high volume scenario and very well in the low volume scenario will also leave a very good mark in a mid volume environment. For a detailed discussion of volume flexibility of a process, see Appendix B.

Chapter 4

Decision Mechanisms and Categorization of Flexibility Strategies

As shown in Chapter 2 there are eleven types of flexibilities, following the argumentation of Sethi and Sethi [SS90]. Chapter 3, on the other side, reveals that for different production program characteristics, e.g., part mix, production volume, part dimensions, etc., some manufacturing processes are more beneficial than others. Thus, in this chapter, a synthesis of the two previous chapters is made. The definitions in Chapter 2 of the different types of flexibilities and the characteristics of processes, as discussed in Chapter 3, are combined to propose two things. First, derived from the results of the 'lever problem', a scheme for the choice of an appropriate manufacturing process for given parts' characteristics is introduced. Second, as an outcome of this scheme, an attempt for a categorization of flexibility types according to the same parts' characteristics is made.

4.1 Decision Mechanisms

The long-term objective for the decision mechanisms proposed in this section, is an expert system, which, given some characteristics of a part, chooses the most adequate manufacturing process. It is obvious that the following approach is far away from that expert system, but, if it can provide further research with some ideas, the short-term objectives are fulfilled.

The methodology chosen for this approach is the *criteria comparison analysis* as described by Raggenbass [Rag03]. First, the influence of the chosen parts' characteristics on manufacturing processes are analyzed isolated from each other. This gives a neutral assessment of beneficial processes for every parameter on the input side. For every pair a criteria comparison with the constant sum 3 is made, see Figure 4-1. Here, the processes *Machining* and *Forming* are set in relation to the input attribute

Attribute	Characteristic	Machining	Forming
Volume	High	1	3
	Low	2	0

Figure 4-1: Criteria comparison for one input parameter and two processes

volume. As can be seen, machining is better for low volumes than for high demands, but forming is only useful with high volumes. It is important to notice, that the processes are compared separately, i.e., forming is not three times better for high volumes than machining, but forming's potential is strongly on the high volume side while machining's potential is slightly on the low volume side.

The parts' attributes serving as input parameters are combined in two groups, *market* and *part*. The first six of the characteristics in the list below deal with influence from the market side, while the other four are related to the part itself. The attributes are defined as follows:

- *Volume* gives a general statement about the volume level at which a part is produced. It can take the two values *high* and *low*. The distinction here is made in the sense of automotive and aerospace volumes. A process with a high output rate is advantageous if volume is high.

- *Demand fluctuation* says whether the fluctuation of the demand in a certain period is *high* or *low*. A process with relatively higher fix and lower variable costs is advantageous if demand fluctuation is high.

- *Product mix* defines the number of parts in the same product family. I.e., not the product mix of a whole firm is concerned, but the chance that a similar product will be produced with the same equipment. The product mix can be *big* or *small*, where big refers to a lot of similar parts, and small to only a few similar parts. A process with a high machine flexibility is advantageous if product mix is big.

- *Stability of part set* expresses the chance, that the current product mix will be changed in the near future. *High* stands for a robust product mix, i.e., the parts in the next period and in the one after the next will be more or less the same as in the current period. *Low*, on the other side, characterizes a volatile product mix. A process with multipurpose tools is advantageous if stability is low.

- *Speed of change* estimates the frequency of changes at the part. If one modification follows the last in short, the speed of change is *high*. Otherwise, if the part remains 'stable' the speed of change is *low*. A process with low fix costs is advantageous if speed of change is high.

- *Speed of reaction* states how fast a modification at the part or product mix must be made to remain competitive. It is *high* if the product must be able to be produced as soon as the (re-)design is finished. If the firm has some time for the introduction for the new or changed part, speed of reaction is *low*. A process with a high product flexibility is advantageous if speed of reaction is high.

- *Parts' size* relates to the part's size. The distinction between *big*, the part needs a lot of space and is difficult to handle, and *small* is made. A process with a huge free space is advantageous if parts' size is big.

- *Dimensionality* refers to the part's shape. It can be *two dimensional*, e.g. metal sheet, or *three dimensional*. A process with a liberty of action in three axes is advantageous if dimensionality is three.

- *Complexity of part* states whether a part is 'simple', then complexity is *low*, or 'tricky', so that complexity is *high*. A process with tight tolerances is advantageous if complexity is high.

- *Load requirement* considers the function of the part. Sometimes, specific load requirements demand a process in which the material's structure is not disturbed. A non-cutting process is advantageous if there are specific load requirements.

The analyzed manufacturing processes are similar to those in Figure 1-3, expanded by *forging*:

- *Machining* includes milling, turning, and other cutting technologies.

- *Forming* subsumes deep drawing, stamping, molding, hydro forming, e.g., the processes *Progress dedicated tool*, *Progress adjustable tool*, and *Infeed* in the lever problem. Generally, processes with high fix costs for tooling, low variable costs, and high output rates.

- *Punching* stands for all die cutting processes with versatile tools.

- *Casting* here especially stands for casting with a lost form, but some reusable tools or cores have to be bought.

- *Rapid prototyping* includes several technologies with which one can produce a few parts very quickly.

- *Laser beam cutting* as defined in the lever problem.

- *Water jet cutting* is more or less the same as laser beam cutting, but for thicker sheets.

- *Forging* in this content refers to drop-forging.

Of course, the list of attributes is not complete and its classifications are only very rough and have to be adjusted and specified to the real problem by the user. The generated table can be seen in Figure 4-2. The part's characteristics are listed on

	Attribute	Weight	Characteristic		Machining	Forming	Punching	Casting	Rapid Prototyping	Laser beam cutting	Water jet cutting	Forging
Market	Volume	14	High		1	3	0	0	0	0	0	1
			Low		2	0	3	3	3	3	3	2
	Demand fluctuation	5	High		1	2	1	1	0	1	1	2
			Low		2	1	2	2	3	2	2	1
	Product mix	9	Big		3	0	2	3	3	3	3	1
			Small		0	3	1	0	0	0	0	2
	Stability of part set	7	High		1	3	1	2	0	0	0	2
			Low		2	0	2	1	3	3	3	1
	Speed of Change	12	High		2	0	2	0	3	2	2	1
			Low		1	3	1	3	0	1	1	2
	Speed of Reaction	3	High		3	0	3	1	3	3	3	1
			Low		0	3	0	2	0	0	0	2
Part	Parts' size	10	Big		1	2	0	1	2	1	1	1
			Small		2	1	3	2	1	2	2	2
	Dimensionality	20	2D		0	1	3	1	2	3	2	1
			3D		3	2	0	2	1	0	1	2
	Complexity of Part	10	High		3	2	0	3	2	2	2	1
			Low		0	1	3	0	1	1	1	2
	Load Requirement	10	Yes		1	3	1	3	0	1	2	3
			No		2	0	2	0	3	2	1	0
Sum					0	0	0	0	0	0	0	0
Rank												

Figure 4-2: Criteria comparison analysis for manufacturing processes

the left side. They are weighted in order to emphasize some specific attributes. This weighting is made by a simple pairwise comparison and a following scaling to hundred.

Now, if a manufacturing process has to be determined for a (new) part, the part's characteristics have to be filled in the empty column between *Characteristics* and the first process. '1' stands for 'true' and '0' for 'false', but also values like '0.7 - 0.3' are possible (the sum must be 1). Afterwards every process' attribute is multiplied by the parts' characteristic and the weight. Finally, all those numbers are summed for each process and ranked. The process with the highest score is best for manufacturing that part. It is obvious, that a system as simple as this one, cannot take off the engineer's decision, but there is a high chance, that one of best three processes actually will be used for the manufacturing of the part. Some examples are made to test the framework and to give an idea how it works. See Appendix G for the results. The table itself with the examples can be found on the CD, see Appendix H, as an 'interactive' Microsoft Excel spreadsheet.

In analogy to the table proposed here, a firm can use a similar spreadsheet for categorizing its available (and future) process technologies and its current (and future) parts. Then, if searching for a manufacturing process for a new product, this criteria comparison analysis proposes possible, or the best, process for manufacturing the part.

4.2 Categorization

The next step is to build the same scheme for different types of flexibilities instead of the manufacturing processes. The idea behind this approach is, that a firm, given a part set, can see which type of flexibility should be considered the most.

The same table as in Figure 4-2 is used. But, instead of the part's size, *parts' sizes range* is regarded. It can be *wide* for a part family with tiny and very big parts, or *small* when all parts in the family are more or less the same size. An open question is *load requirement*. As can be seen in Figure 4-3 this attribute is indifferent to the various flexibilities. But, in order to open the discussion about this fact, it is not removed from the table.

This table is read in the way that, if an input parameter with a certain value occurs, a type of flexibility with high ranking is most supportive to that attribute. E.g., for a product with a high volume, volume flexibility is not that important as for a product with a low volume because for a high volume product the cost curve is normally flatter (see Section 2.2.1) and an effort in increasing volume flexibility brings not the same profit than putting the same resources in the low volume case. But, if the demand fluctuation is high, volume flexibility should be of major concern. It has to be acknowledged that a lot of implicit knowledge, acquired while working on this thesis, entered the development of the criteria comparison analysis. So, the values found in the table have a strong subjective touch, and perhaps are not traceable in

	Attribute	Weight	Characteristic		Machine Flexibility	Material Handling Flexibility	Operation Flexibility	Process Flexibility	Routing Flexibility	Product Flexibility	Volume Flexibility	Expansion Flexibility	Program Flexibility	Production Flexibility	Market Flexibility
Market	Volume	3	High		1.5	1.5	1.5	1.5	1.5	1.5	1	1.5	3	1.5	1.5
			Low		1.5	1.5	1.5	1.5	1.5	1.5	2	1.5	0	1.5	1.5
	Demand fluctuation	20	High		2	1.5	2	1.5	2	1.5	3	2	2	1.5	2
			Low		1	1.5	1	1.5	1	1.5	0	1	1	1.5	1
	Product mix	10	Big		3	3	2	3	2	1.5	2	2	3	3	1
			Small		0	0	1	0	1	1.5	1	1	0	0	2
	Stability of part set	17	High		1	1	1.5	1	1.5	0	1	1	1	1	1
			Low		2	2	1.5	2	1.5	3	2	2	2	2	2
	Speed of Change	7	High		3	2	2	2	2	3	1.5	1.5	1.5	2	2
			Low		0	1	1	1	1	0	1.5	1.5	1.5	1	1
	Speed of Reaction	13	High		2	2	1.5	2	1.5	3	1.5	1.5	1.5	2	2
			Low		1	1	1.5	1	1.5	0	1.5	1.5	1.5	1	1
Parts	Parts' Sizes Range	12	Wide		2	2	1.5	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			Small		1	1	1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Dimensionality	9	2D		1.5	2	1.5	2	1.5	1	1.5	1.5	1.5	1	1.5
			3D		1.5	1	1.5	1	1.5	2	1.5	1.5	1.5	2	1.5
	Complexity of Part	6	High		2	2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	1.5
			Low		1	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1.5
	Load Requirement	3	Yes		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			No		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sum					0	0	0	0	0	0	0	0	0	0	0
Rank															

Figure 4-3: Criteria comparison analysis for types of flexibilities

detail.

Notice that the weightings for the input attributes changed to emphasize other characteristics than in the first analysis. The weighting is made in the same way with the pairwise comparison.

Also for the second analysis, some examples can be seen in Appendix G.

Chapter 5

Summary and Conclusions

5.1 Summary

In order to summarize a large literature survey, a short introduction into the field of manufacturing flexibility is provided. It is shown that *flexibility* is the last of the three major concerns in manufacturing which are *efficiency*, *quality*, and *flexibility*. Flexibility emerged in the second half of the last century driven by the uncertainties and instabilities in the 1970s and 1980s. The customers' needs to a wider variety of products, customized for their specific purposes, forced manufacturers to implement some kind of flexibility.

The term 'flexibility' is still vague and diffuse. That is shown by the huge number of different, and some times controversial, taxonomies of manufacturing flexibilities. To make a clear distinction between different types of flexibilities and their impact in manufacturing concepts, the classification scheme made by Sethi and Sethi [SS90] is adopted and discussed. Eleven flexibilities, machine, material handling, operation, process, routing, product, volume, expansion, program, production, and market flexibility, are defined and discussed. Some other approaches are presented, not to overtake those definitions, but to show how other authors built up their frameworks, which may in some cases be more precise and significant than the one made by Sethi and Sethi. Also two possibilities for valuing flexibility are conferred. The results of several interviews show, that even today, flexibility has a different meaning to different people. The two environments 'aerospace industry' and 'automotive industry' are characterized according to the statements made by the interviewees. An outcome of this whole discussion is, that flexibility can only bring its profits when it is *cultivated* as an integrated system.

After having described the state of the art in manufacturing flexibility, the business case 'the lever problem' is worked out to show how different market and product aspects influence the decisions for the manufacturing processes. Uncertainty is modeled in three market scenarios, each with different products and demand fluctuations. These market scenarios are combined with six different process scenarios, each modeling a different manufacturing process. This is done for both, the automotive and the aerospace environment. It can be shown that not only the expected earnings of a production decision must be considered, but also other factors like risk of obsolete technology (capital bound in no longer used tools) or opportunity costs (machine availability for other productions). It is evident that the best manufacturing processes in the automotive case are not the same as the best processes in the aerospace model. A simulation model as built for this analysis can also be used to simulate other uncertainties, such as new regulations, increase in labor costs, or shifts in market powers.

The criteria comparison analysis derived from the precedent results states a possible solution for choosing an adequate manufacturing process if some parts' characteristics are known. An other application of this methodology is a framework that shows, given the product set's characteristics, which type of flexibility is most beneficial for the firm, and therefore should be concerned the most.

5.2 Conclusions

This thesis shows that flexibility in part manufacturing is a complex topic. Flexibility can either be embedded in the part itself, in the manufacturing process, or both, see Figure 5-1. If flexibility is implied in the process, it can either be embedded in the tools or in the process parameter and raw materials, or both. The first case is illustrated

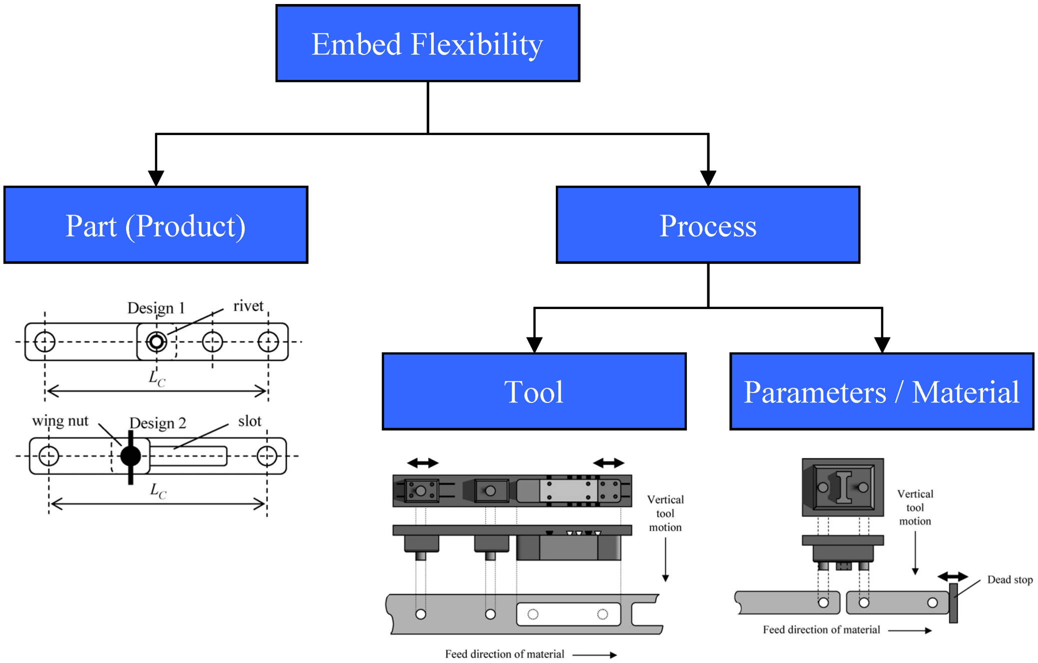

Figure 5-1: Different ways to embed flexibility

by the different designs for the levers which expresses flexibility in the part itself. The second situation, flexibility in the tool, is presented by the concept of modular tooling in which the tool is suited to match the requirements of the process. This is shown with the process scenario *Progress adjustable tool*. In the third case, flexibility is embedded in the process parameters and in the raw materials. The process scenario *Infeed* acts as an example for this purpose.

The results also show that maximal flexibility is not most profitable. In Figure 5-2 the earnings of the different process scenarios are compared relatively to each other. While in the low volume scenario all analyzed processes make more or less equal earnings, in the high volume case, only fast processes can run profitably. Even though *Laser beam*, *Punching*, and *Milling* possess higher process flexibility than the other three, it is obvious that this flexibility is no longer profitable at higher volume levels. So the variety of part's characteristics must be reduced to one or two dimensions. Then flexibility can easier be embedded in processes which are high volume capable. The key question, then, is how to determine those one or two dimensions which should be designed to be flexible.

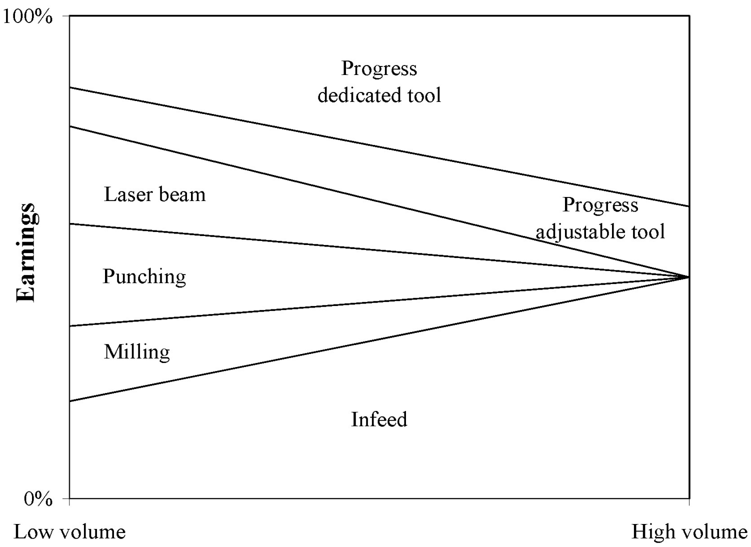

Figure 5-2: Earnings of processes versus number of units produced

With this thesis, also an attempt to answer several questions, see Section 1.1.2, is made. As a recapitulation, these are now, at least partially, answered:

- State of the art in flexible component manufacturing systems is, in the automotive industry, forming technology. The high volumes demand high output rates and high investments in fix costs are worth in order to get low variable costs. In the aerospace industry, currently a shift from assembling several simple parts, manufactured by forming technology, to producing directly complex end-products by machining can be observed. The firms are willing to invest huge amounts of money to install multi-axes cutting machines which are run three shifts and seven days a week.

- Best practice in stamping technology are output rates of 50 to 80 parts per minute for complex parts at relatively big sizes and 250 to 300 parts per minute for simple and small parts.

- The most common strategy to increase capacity when needed is by adding shifts. A good compensation model is the concept of the annual working time in which overtime can be compensated during low output phases.

- The ratio of fix to variable costs can be used to express volume flexibility of a manufacturing system. The flatter the cost curve the higher the volume flexibility. The exact crossover points of the cost curves of different processes need to be determined with real data. A general approach is discussed in Section 1.1.1.

- A process' flexibility in terms of part geometries refers to machine, material handling, process, and product flexibility. It is obvious that machining in general reaches higher levels in those flexibilities than forming. Nevertheless, flexibility must be seen in the whole context and therefore be optimized as a whole system.

- Simulation support can be very useful while attempting to increase flexibility. Since flexibility of manufacturing systems is a complex construct, it is difficult to understand it without any models. An other often discussed concept, modular tooling, is only profitable at very low output level and is used mostly only to manufacture prototypes.

- The proposed framework of the criteria comparison analysis can serve as a 'tool' to choose the best types of flexibilities to invest in. The outcome then should be an optimized allocation of flexibility of a manufacturing system.

- A firm's need to adopt customers' demands as quickly as possible call for flexible systems. But, flexibility will not be a free good. Flexible solutions need major investments and reorganization.

Flexibility in aerospace and automotive component manufacturing systems: practice, strategy and optimization, which is the title of this thesis. In Chapter 2, the practice of current manufacturing systems are presented by a list of literature about flexibility in manufacturing and several interviews with people for whom flexibility in manufacturing is a daily challenge. Some possible strategies how to manufacture the 'simple' lever in two different market environments are affiliated in Chapter 3. Finally, in Chapter 4, a suggestion of an 'optimizer' for flexibility in manufacturing systems is made. But, even if this thesis highlights lots of starting points, further research has to be done to make today's manufacture of simple parts and complex systems more and more flexible.

5.3 Further Research

As already mentioned above, research must go toward an *integrated optimization and discussion framework* for flexible component manufacturing systems. The concept of *multidisciplinary design optimization* will be very valuable to approach this challenge.

First, experts should agree on clear cut definitions of the different types of flexibilities. This will simplify further work since all the 'translation' effort will drop out. Then, a more accurate framework for the measurement of flexibility can be built. The simulation methodology compiled in this thesis can serve as a basis for a wider supporting system on valuing flexibility which will help to compare different flexibility strategies.

Based on the process scenario *Infeed*, further research on flexibility in the process parameters and raw materials must be done. A methodology for determining the crucial dimensions of a part, in regards to keep them flexible, will be very useful in order to design processes with the according tools to manufacture those parts.

Mills' quadratic cost function deserves some more research, considering the analysis of those parameters α, β, and δ. A table which provides these constants for a huge choice of current manufacturing processes will help production managers and engineers to determine best manufacturing processes for their parts.

The criteria comparison analysis seems to be a useful instrument. But to get it really reliable, further work has to be done to find more input parameters and to approve or reset the dependency values for the process choice as well as for the flexibility type choice table.

Chapter 6

German Summary – Deutsche Zusammenfassung

In diesem Kapitel werden die wichtigsten Punkte dieser Diplomarbeit in deutscher Sprache hervorgehoben. Die Überschriften beziehen sich auf die einzelnen Kapitel dieser Arbeit.

6.1 Einleitung

Eine kurze Einführung in das Gebiet der Fertigungsflexibilität zeigt, dass Flexibilität in der zweiten Hälfte des letzten Jahrhunderts als letzte der drei grössten Herausforderungen an die Fertigungsorganisation entstanden ist. Diese sind *Effizienz*, *Qualität* und *Flexibilität*. Vor allem die Unsicherheiten und Instabilitäten der 1970er und 1980er Jahre förderten das Flexibilitätsdenken. Die Kunden verlangten eine immer grössere Vielfalt an Produkten, angepasst an ihre spezifischen Bedürfnisse, die die Hersteller zur Integration von Flexibilität in ihre Produktion zwang.

6.2 Literatur

Die Literaturrecherche bringt einerseits verschiedene Konzepte über Fertigungsflexibilität zum Vorschein zeigt aber andererseits auch, dass der Begriff Flexibilität immer noch ambivalent und sehr diffus ist. Dies ist vor allem an den vielen verschiedenen, und zum Teil widersprüchlichen, Definitionen von Flexibilität zu erkennen.

Eine der umfangreichsten Klassifizierungen von Flexibilitätsarten wurde von Sethi und Sethi [SS90] gemacht. Deshalb verwendet dieser Bericht ausschliesslich deren Definitionen. Es werden elf verschiedene Typen von Flexibilität unterschieden: Maschinen-, Material-Handling-, Herstellungs-, Prozess-, Routen-, Produkt-, Volumen-, Erweiterungs-, Produktions- und Marktflexibilität. Eine Übersicht über die Definitionen, den Nutzen, die Voraussetzungen und die Messung von den besprochenen Flexibilitätsarten ist in Anhang A enthalten. Der Vollständigkeit halber werden einige weitere Konzepte vorgestellt, sie mögen als wertvolle Hinweise für eine genauere Klassifizierung oder Analyse dienen.

Ebenfalls präsentiert werden die Ergebnisse aus den Interviews, die im Rahmen dieser Diplomarbeit geführt wurden. Diese Gespräche zeigen, dass Flexibilität auch in der Praxis heutzutage noch verschiedene Bedeutungen hat. Aus den Aussagen der Befragten werden schliesslich zwei Marktumgebungen, *Automobil-* und *Luftfahrtindustrie* charakterisiert, die als Grundlage für die weiteren Untersuchungen in dieser Arbeit dienen.

Die Kernaussage aus diesem Kapitel ist, dass Flexibilität nur einen Nutzen bringt, wenn sie als integriertes System gepflegt wird und entsprechend in der Unternehmenskultur verankert ist.

6.3 Das Hebelproblem

Als nächster Schritt wird die Fallstudie 'Das Hebelproblem' bearbeitet. Darin steht eine Firma vor der Entscheidung wie sie ihre Produkte (einfache Metallhebel) flexibler herstellen kann, um damit besser auf Nachfrageveränderungen reagieren zu können. Ungewissheit von der Marktseite ist mittels drei Marktszenarien modelliert, jedes mit einem anderen Produktemix und anderen Nachfrageschwankungen. Diesen Marktszenarien werden sechs Prozessszenarien gegenüber gestellt, jedes eine andere Prozesstechnologie beschreibend. So entstehen 18 verschiedene Fälle, die alle sowohl für die Automobil- als auch für die Luftfahrtindustrie modelliert, simuliert und analysiert werden. Bei der Herleitung der Lösung werden viele Faktoren, die berücksichtigt werden müssen, erläutert und untersucht. Es wird auch gezeigt, dass bei der Evaluation eines Fertigungsprozesses nicht nur der erwartete Gewinn, sondern auch Risikofaktoren, wie z.B. in Werkzeugen gebundenes Kapital, oder Opportunitätskosten von Bedeutung sind. Die Ergebnisse machen deutlich, dass der optimale Prozess in einem hochvolumigen Umfeld nicht der gleiche ist wie die beste Fertigungsart in einem Marktumfeld mit einem niedrigeren Absatz.

Die in diesem Kapitel vorgestellte Methodik zur Analyse der verschiedenen Prozesse kann ebenso gut verwendet werden für die Untersuchung von anderen Unsicherheiten wie z.B. neuen Gesetzen, Veränderung in Lohnkosten oder die Verschiebung von Marktkräften.

6.4 Ergebnisse

Die gewonnen Erkenntnisse werden mit Hilfe einer Kriterienvergleichsanalyse kategorisiert. So ensteht ein Modell, mit dem anhand von Merkmalen des Produkts der optimale Fertigungsprozess abgeleitet werden kann. Ein analoges System für die Auswahl von kritischen Flexibilitätsarten für die Herstellung des Produkts wird anschliessend vorgestellt. Die in dieser Arbeit vorgestellte Lösung erreicht das Fernziel von einem Expertensystem noch lange nicht, dient aber hoffentlich als Grundlage für weitere Forschungen.

Die Arbeit als Ganzes zeigt, dass Flexibilität in der Komponentenherstellung ein sehr komplexes Thema ist. Flexibilität kann entweder im Produkt selbst oder im Herstellungsprozess, oder in beiden, eingebunden werden. Falls Flexibilität im Prozess vorhanden ist, kann man weiter zwischen Flexibilität im Werkzeug und Flexibilität in den Prozessparametern unterscheiden, siehe hierzu Abbildung 5-1. Es wird deutlich, dass maximale Flexibilität nicht die profitabelste Lösung ist. Die Resultate zeigen, dass Flexibilität auf eine oder zwei Produktdimensionen (z.B. die Länge des Hebels im Hebelproblem) reduziert werden sollte. Damit ist die Wahl und auch die Anwendung eines (optimalen) Produktionsprozesses vereinfacht. Die Kernfrage ist dann jedoch, wie diese eine oder zwei charakteristischen Produktdimensionen bestimmt werden können.

Appendix

Appendix A

Types of Flexibilities – Overview

As a summary of the discussed types of flexibility the following table combines definition, purposes, means, and measurement of the eleven flexibilities. Figure A-1 provides the English version, and Figure A-2 is the German edition. The colors indicate whether a flexibility type is a basic or component flexibility, a system flexibility, or an aggregate flexibility. The same colors are also used in Figure 2-2.

Types of flexibilities (according to Sethi and Sethi, 1990)

Type	Definition	Purposes	Means	Measurements
Machine flexibility (of a machine)	Refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another	Is necessary for other flexibilities. Allows lower batch sizes, savings in inventory costs, higher machine utilizations, production of complex parts, shorter lead time for new product introduction, better quality realization	Numerical control, accessible programs, sophisticated part loading and tool-changing, FMS	Number of different operations that a machine can perform without requiring more than a specified amount of effort. Number of tools, number of programs that the machine can use
Material Handling flexibility (of a system)	The systems ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves	Increases availability of machines and thus reduces throughput times	Having transporting devices like forklift trucks, push carts and an appropriate layout design. Automated guided vehicles, robots, computer controls. General-purpose fixtures	Ratio of number of paths that the system can support to the number of paths supported by the universal system
Operation flexibility (of a part)	Refers to a parts ability to be produced in different ways	Easier scheduling, increases machine availability and utilization	Design of the part, modular parts	Number of different processing plans for its fabrication
Process flexibility (of a manufacturing system) = Mix flexibility	Relates to the set of part types that the system can produce without major setups	Reduction of batch sizes and inventory costs	Derives from machine flexibility, material flexibility, operation flexibility	Volume of set of part types (group technology concepts, range of sizes, shapes…)
Routing flexibility (of a manufacturing system)	A manufacturing system its ability to produce a part by alternate routes through the system	Efficient scheduling of parts by better balancing of machine loads. Also at events as machine breakdowns	By having multipurpose machines, machines with overlapping process envelopes, and operation flexibility of parts	The average number of possible ways in which a part type can be processed in the given system
Product flexibility (of a manufacturing system)	The ease with which new parts can be added or substituted for existing parts, so, the part mix currently being produced can be changed inexpensively and rapidly	Allows the company to be responsive to the market by enabling it to bring newly designed products quickly to the market	Depends on machine flexibility, material handling flexibility, operation flexibility, CAD/CAM	Time or cost required to switch form one product mix to another, not necessarily of the same part types
Volume flexibility (of a manufacturing system)	The ability of the system to be operated profitably at different overall output levels	Allows the factory to adjust production upwards or downwards within wide limits	Low variable costs and relatively higher fix costs. JIT	The range of volumes in which the firm can run profitably
Expansion flexibility (of a manufacturing system)	The ease with which the systems capacity (output rate) and capability (quality, technological state, etc.) can be increased when needed	Help reducing implementation time and cost for new product. Important for growth strategies, new markets	Small production units, modular flexible manufacturing cells, multipurpose machinery, high level of automation for mounting additional shifts	The overall effort and cost needed to add a given amount of capacity. E.g. the cost for doubling the capacity
Program flexibility (of a system)	The ability of a system to run virtually untended for a long enough period	Reduction of throughput time by having reduced setup times. Increases the effective capacity of the production system	Depends on process and routing flexibilities and on having sensors and computer controls	Expected percentage uptime during the second and third shifts. Scaling automation level
Production flexibility (of a system)	Is the universe of part types that the manufacturing system can produce without adding major capital equipment	Allows the firm to compete in a market where new products frequently demanded. It permits an increase of part families and allows the firm to diversify its risk	The variety and the versatility of the machines that are available, the flexibility of the handling system in use, the factory information and control system	Number of parts the system is capable of producing. Shadow prices (Jaikumar)
Market flexibility (of a system)	Is the ease with which the manufacturing system can adapt to a changing market environment	Is essential if the firm's marketing strategy emphasizes customized products and frequent product changes	Requires that the process of production planning and inventory controls be closely integrated with such marketing functions as market forecast, product development, and customer relations	A weighted measure of efforts in terms of time and cost required to introduce a new product, to in- or decrease production volume

Figure A-1: Types of flexibilities according to [SS90]

Flexibilitätsarten (nach Sethi und Sethi, 1990)

Art	Definition	Nutzen	Voraussetzungen	Messung
Maschinenflexibilität (einer Maschine)	Die Vielfalt von Arbeitsgängen die eine Maschine ausführen kann, ohne einen übermässigen Rüstaufwand	Maschinenflexibilität ist nötig für andere Flexibilitätsarten. Sie erlaubt kleinere Losgrössen, Einsparungen in Lagerbeständen, höhere Ausnutzungsgrade, Herstellung von komplexeren Teilen, kürzere Einführungszeit von neuen Produkten und bessere Qualitätserreichung	NC, zugängliche Programme, hochwertige Teilezuführung und Werkzeugwechsel, typisch: FMS	Anzahl der Arbeitsgänge, die eine Maschine ausführen kann ohne dass der Rüstaufwand eine definierte Grösse übersteigt. Anzahl der Werkzeuge oder Programme die die Maschine benutzen kann
Material-Handlingsflexibilität (eines Systems)	Die Fähigkeit eines Systems verschiedene Teile effizient zu transportieren und genau zu positionieren	Erhöht die Maschinenverfügbarkeit und reduziert die Durchlaufzeit	Transportmittel wie Hubstapler oder Handwagen, angepasstes Layout. Führerlose Transportsysteme, Roboter, Computersteuerung. Universelle Fixaturen	Verhältnis der Anzahl Wege die das Material-Handling System benutzen kann zur Anzahl der total möglichen Wege im System
Herstellungsflexibilität (eines Teiles)	Die Fähigkeit eines Teiles auf verschiedene Arten hergestellt werden zu können	Vereinfachte Planung, erhöhte Maschinenverfügbarkeit und höhere Auslastung	Teilekonstruktion, modulare Teile	Anzahl der Operationspläne für die Herstellung eines Teils
Prozessflexibilität (eines Produktionssystems)	Die Menge der Teilearten, die ein System herstellen kann ohne übermässigen Rüstaufwand	Reduktion der Losgrösse und Senkung der Lagerbestände	Abhängig von Maschinen-, Material-Handlings- und Herstellungsflexibilität	Volumen der Teilefamilien (Gruppentechnologiekonzepte, Grössenbereiche, Formen, ...)
Routenflexibilität (eines Produktionssystems)	Die Fähigkeit eines Produktionssystems, Teile auf verschiedenen Wegen durch das System herzustellen	Effizientes Planen dank ausgeglichenerer Maschinenauslastung. Reaktionsfreiheit bei Maschinenausfall	Mehrzweckmaschinen mit überlappenden Prozessmöglichkeiten und Herstellungsflexibilität der Teile	Die durchschnittliche Anzahl von verschiedenen Wegen, auf denen ein Teil produziert werden kann
Produktflexibilität (eines Produktionssystems)	Die Einfachheit mit der neue Teile zum Sortiment hinzugefügt, oder bestehende Teile ersetzt werden können. Der bestehende Produktemix kann einfach und schnell geändert werden	Erlaubt, schnell auf Marktveränderungen einzugehen mit kurzen Produkteinführungszeiten	Abhängig von Maschinen-, Material-Handlings- und Herstellungsflexibilität und CIM-Einsatz	Zeit oder Kosten, die benötigt werden um von einem Produktmix zu einem anderen (nicht notwendigerweise der gleichen Teilefamilie) zu wechseln
Volumenflexibilität (eines Produktionssystems)	Die Fähigkeit bei unterschiedlichen Volumen profitabel zu produzieren	Erlaubt der Firma die Produktion nach oben und unten in einem grossen Bereich anzupassen	Tiefe variable Kosten und eher höhere Fixkosten, JIT	Der Volumenbereich in dem die Firma profitabel produzieren kann
Erweiterungsflexibilität (eines Produktionssystems)	Die Leichtigkeit mit der die Kapazität und Qualität falls nötig erhöht werden kann	Hilft Produkteeinführungszeit und -kosten zu reduzieren. Wichtig für Wachstumstrategien und in neuen Märkten	Kleine Produktionseinheiten, Flexible Fertigungszellen, Mehrzweckmaschinen, hoher Automatisierungsgrad für zusätzliche Schichten	Gesamtaufwand um zusätzliche Kapazitäten zu ermöglichen. Z.B. Kosten um die Kapazität zu verdoppeln
Programmflexibilität (eines Systems)	Die Fähigkeit eines Systems unbeaufsichtigt lange Zeit produzieren zu können	Reduktion der Durchlaufzeit dank kürzeren Rüstzeiten. Erhöht die effektive Kapazität des Systems	Abhängig von Prozess- und Pfadflexibilität, Sensoren und Computersteuerung	Erwartete prozentuale Kapazitätssteigerung während der zweiten und dritten Schicht. Oder Automatisierungsgrad
Produktionsflexibilität (eines Systems)	Die Gesamtheit aller Teilefamilien die ein System produzieren kann ohne zusätzlichen Kapitalaufwand	Wettbewerbsfähigkeit in Märkten mit häufigen Produktewechseln. Mehrere Teilefamilien und Diversifikation des Risikos	Unterschiedliche und vielfältige Maschinen, Material-Handlingsflexibilität, Informations- und Steuerungssysteme	Anzahl der zu produzieren möglichen Teile. Oder Schattenpreise für zusätzliche Teile
Marktflexibilität (eines Systems)	Die Leichtigkeit mit der das System sich veränderten Märkten anpassen kann	Notwendig für kundenspezifische Marketingstrategie und häufig wechselnde Produkte	Produktions- und Lagerplanung müssen eng mit Marketing, Produkteentwicklung zusammenarbeiten	Gewichtete Messung von Zeit oder Kosten für Produkteeinführungen, oder Veränderung des Produktionsvolumens

Figure A-2: Flexibilitätsarten nach [SS90]

Appendix B

Volume Flexibility

B.1 Introduction

As already stated in the paragraph about volume flexibility, see Section 2.2.1, volume flexibility can be achieved by going for low variable costs and accepting, perforce, higher fixed costs. Nevertheless, low fixed *and* low variable costs would be the utopia aim. Since the literature about volume flexibility is somewhat confusing, the results of further research about the influence of fixed and variable costs on volume flexibility are discussed here.

Before starting, some terms need to be defined. *Total cost* is the sum of costs for a certain output volume, i.e. the sum of the variable cost multiplied with the number of produced units and the fixed cost. The *average cost* then is defined as the total cost per part, i.e., the total cost divided by the corresponding number of output units. The *marginal cost* expresses the cost of the last produced unit, i.e., they can be calculated as the difference of total cost at output n and the total cost at output $n-1$, if n stands for the current number of produced units.

Assuming the cost model that consists only of fixed and constant variable costs components, it is obvious that marginal costs are equal to the (constant) variable cost per part. Average costs decrease strictly with the increase of the output volume and approach asymptotically the marginal costs. This concept is known as 'economics of scale', i.e. accounting for the learning curves the variable costs per part can be lower at higher volumes. But this concept comes only true, if a firm is completely divisible[1] and adaptable[2], as Stigler [Sti39] noted. This is mainly true in the long-run.

But in the short-run, a machine (or plant) is neither divisible nor adaptable. Then the law of diminishing returns brings another effect on the characteristics of the cost curves. As Gwartney, Stroup, and Sobel [GSS99] write: 'The Law of Diminishing Returns states that as more and more resources (e.g., labor) are devoted to a production process, they increase output but at an ever decreasing rate. For example, if an acre of corn needs to be picked, the addition of a second and a third worker is highly productive. But if you already have 300 workers in the field, the productive capacity of the 301^{st} worker is not near that of the second worker.'

Thus, variable cost increase superproportional with the output. For modeling this situation, Mills [Mil84] uses the quadratic cost function

$$c_t(n) = \alpha + \beta n + \frac{n^2}{2\delta} \tag{B.1}$$

where c_t is total cost, n the production volume, and α, β, and δ are positive constants. The average costs then are

$$c_a(n) = \frac{\alpha}{n} + \beta + \frac{n}{2\delta} \tag{B.2}$$

and the marginal costs, as the derivative of the total costs with respect to the number of units n, are positive and increasing

$$c_m(n) = \frac{\partial c_t(n)}{\partial n} = \beta + \frac{n}{\delta} \tag{B.3}$$

As can be seen, e.g., in [Sch00], average costs decrease as long as they are higher than marginal costs. So the crossover point of average costs and marginal costs is coexistent with the optimal output volume. At that production quantity average costs are lowest. This can be seen in Figure 2-1. This is also true for the model with the constant variable costs, only, average and marginal cost then never cross. It can

[1] Means that a plant can be partly used

[2] Means that a plant's capacity can be expanded or reduced

also be shown by analyzing Mills' cost function. The average costs' low point is at

$$\frac{\partial c_a(n)}{\partial n} \stackrel{!}{=} 0 \Longrightarrow n = \sqrt{2\alpha\delta} \tag{B.4}$$

and for the intersection of the average and the marginal cost curves the same volume is found

$$c_a(n) = c_m(n) \Longrightarrow n = \sqrt{2\alpha\delta} \tag{B.5}$$

In Appendix B.3 the parameters α, β, and δ for three processes in the lever problem are determined in order to obtain the optimal production volume for these processes.

B.2 Cost Structure and Volume Flexibility

An attempt to reconstruct Stigler's concept that '(volume) flexibility is least when marginal costs are steep and average costs rise precipitously around their minimum, flexibility increases as average costs are flatter and marginal costs less steep' is made here. With the definition of volume flexibility 'volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels' the performance of the cost curves is analysed. Therefore some scenarios are built to try to prove the means for volume flexibility 'to go for lower variable costs and accept therefore higher fixed costs'.

A model is built with an imaginary machine. The following input parameters have no relation to any existing machine or concept, but accepting these numbers, charts with the results show clearly how average and marginal cost at different output level change while changing input parameters. The machine is assumed to have a capacity of 1,680 parts per shift. Running the machine in three shift operation, 5,040 parts can be produced per day. Fixed costs remain constant, while variable costs are five (for the second shift) and 10 times (for the third shift) as high as for the first shift. Obviously, not Mills' quadratic cost function is used here, but a simple model with fixed and (stepwise constant) variable costs.

The first analysis is done by holding the fixed cost and varying the variable cost.

Table B.1 shows the input parameters for Figure B-1 which depicts the corresponding average cost curves and the linear regression curve of the marginal costs. As can be

Curve	Fixed Cost	Var Cost
Green	15,000	1
Blue	15,000	2
Orange	15,000	4
Gray	15,000	8

Table B.1: Input parameters for Figure B-1

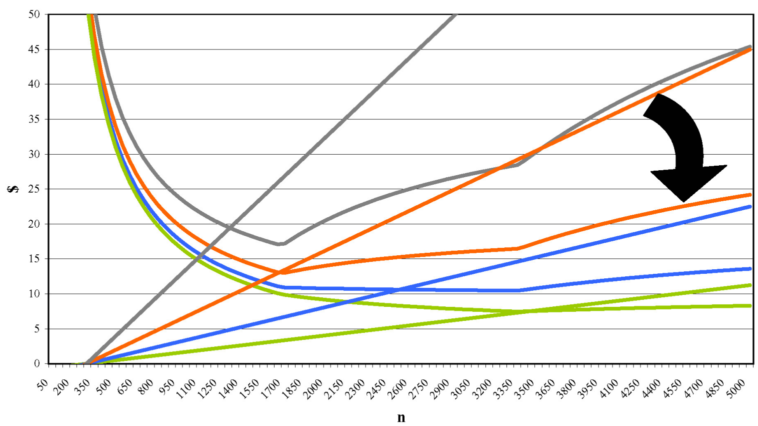

Figure B-1: Average and marginal costs for different variable costs

seen, indicated by the black arrow, the lower the variable costs, the wider the average cost curve and the flatter the slope of the marginal costs. Thus, following Stigler's argumentation, the lower the variable costs the higher volume flexibility. The fact that the marginal cost regression line does not cross the average cost curve exactly at its low point lies in the model with the escalating (and not continuous) increasing variable cost over the output.

The second investigation searches for the behavior of the cost curves, while the variable cost are held and the fixed cost vary. The input parameters and results can be seen in Table B.2 and Figure B-2, respectivley. All combinations of fixed and variable cost have the same marginal costs, i.e., the slope of the marginal cost curve is only dependent on the variable cost and is independent of the fixed cost. As indicated by the black arrow, the lower the fixed cost the more rectangular the average cost curve. This could be interpreted as higher volume flexibility, but demands for further

Curve	Fixed Cost	Var Cost
Green	5,000	2
Blue	10,000	2
Orange	15,000	2
Brown	20,000	2
Gray	40,000	2

Table B.2: Input parameters for Figure B-2

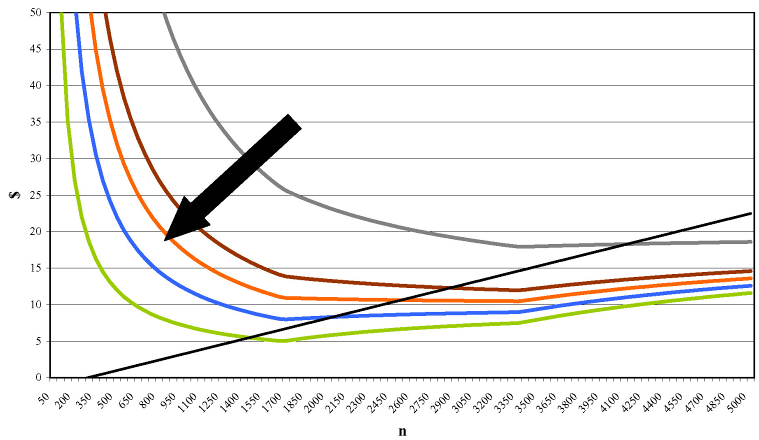

Figure B-2: Average and marginal costs for different fixed costs

research.

This is done by defining 14 'scenarios', each with an other combination of fixed cost (5,000, 10,000, 15,000, and 20,000) and variable cost (1, 2, 3, and 4). (The cases 5,000-3 and 5,000-4 are skipped because the 5,000 series was originally not included, but then was added later for more meaningful results. At that time, the tendency for the variable cost was already clear, so there was no need to extend the research.)

First of all, the information that a process' cost structure defines the optimal output volume is analyzed. As mentioned above, the optimal production volume is at that quantity at which average and marginal cost curves intersect. For all the combinations of fixed and variable costs the average and marginal cost curve is drawn and the optimal production output is read out of the chart. Then the ratio of fixed and variable cost is calculated and compared with the optimal manufacturing quantity. Figure B-3 shows the result. It can be seen clearly that the ratio of the fixed to variable costs determines the optimal production output. So, a low production volume can be satisfied more economically with relatively low fixed and therefore relatively high

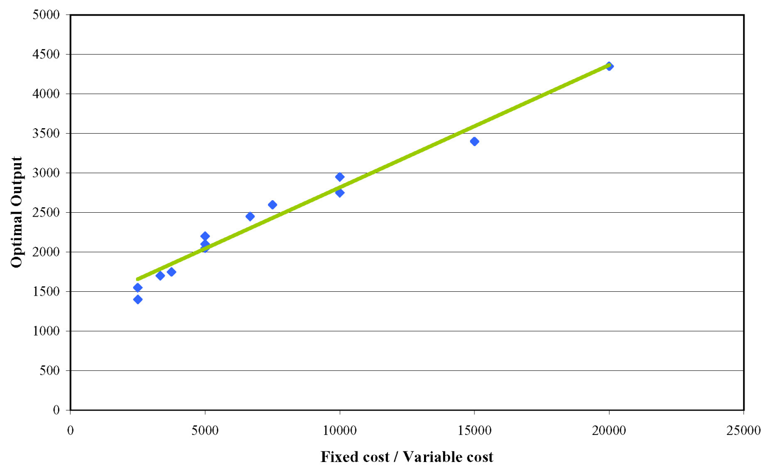

Figure B-3: A process' optimal output volume dependent on its costs structure

variable cost. And, on the other hand, for a high production volume, high fixed and low variable cost are better.

In the second step, volume flexibility as a characteristic of the average and marginal cost curves is tested. Always two pairs of curves are compared optically, i.e., the curvature of the average cost curves and the slope of the marginal costs are laid over each other, and marked as 'better' (more flexible than the other) or 'worse' (less flexible than the other). Then for every 'scenario' the 'betters'-points are added up and the 'worses'-points are subtracted. So the final result is a ranking list which puts the combinations of fixed to variable cost ratios in an order. The higher the ranking the higher the volume flexibility of this 'scenario'. The next three figures show the results. In Figure B-4 a 'scenarios' ranking is drawn dependent on its absolute fixed costs. The trend is not very clear but recognizable, that the lower the fixed costs the higher the ranking, and, thus, the higher the volume flexibility. So, it can be seen that the most flexible process is one with fixed costs of 5,000 and the least flexible process is one with fixed costs of 20,000. Figure B-5 is an analogous chart, but here the ranking of the 'scenario' is recorded to the absolute variable costs. It is obvious that the lower the variable costs the higher the ranking, and, therefore, the higher the volume flexibility. In the last chart, Figure B-6, every bubble stands for a combination of fixed and variable costs and its size represents the rank of this combination. Starting, e.g., at the combination of 15,000-2 (the green bubble in Figure B-6) volume flexibility

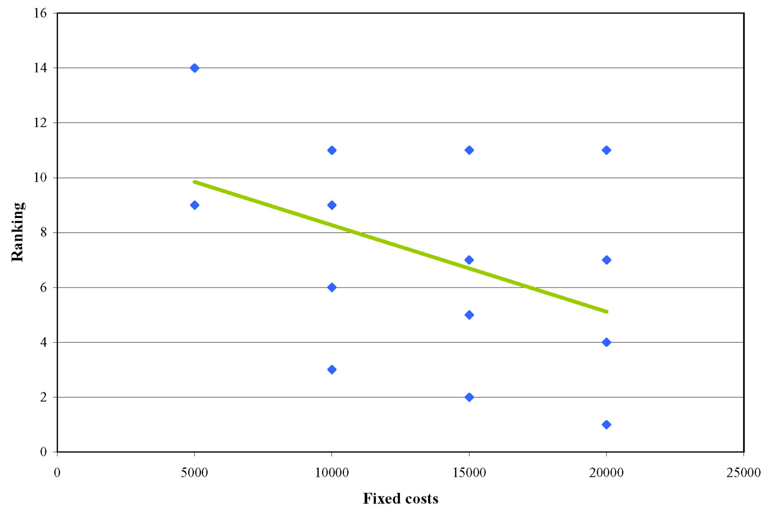

Figure B-4: Volume flexibility dependent on a process' fixed costs

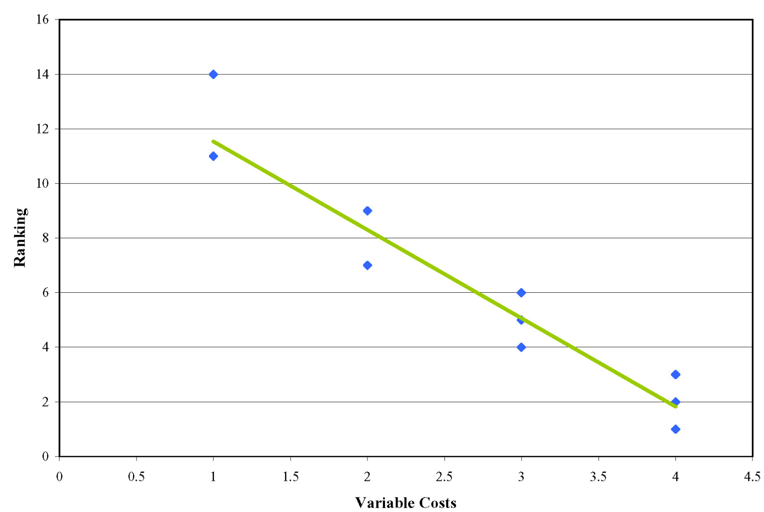

Figure B-5: Volume flexibility dependent on a process' variable costs

can be slightly increased by reducing the fixed costs (go to the left) or significantly increased by reducing the variable costs (go down). Reducing the variable costs and *increasing* the fixed cost (go down and to the right) brings a bigger gain in volume flexibility than just reducing the fixed costs. By following these steps, the ratio of fixed to variable costs changes and therefore also the optimal production output. If volume flexibility should be increased while maintaining the optimal output, fixed *and* variable costs must be reduced (go down and to the left).

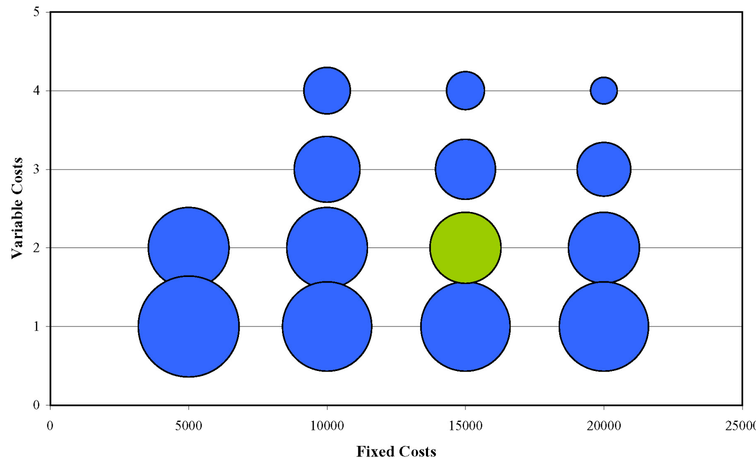

Figure B-6: Volume flexibility dependent on process' fixed and variable costs

B.3 Volume Flexibility in the Lever Problem

As a conclusion of the discussion above, a chart similar to Stigler's cost curves (Figure 2-1) should be reconstructed with data of this thesis. Following Chapter 3, two extreme process scenarios, *Laser beam* and *Progress dedicated tool* as well as *Infeed* are compared now. It should be self-explanatory that *Laser beam's* optimal output is lower and its volume flexibility is smaller than than those of *Progress dedicated tool*. Even though, in the simulation of the lever problem variable costs are assumed to be constant, here the same model as in Section B.2 is used. That means that variable costs in the second and third shift are higher than in the first. Figure B-7 shows the average and marginal cost curves of *Laser beam* (blue), *Progress dedicated tool* (green), and *Infeed* (black) in a logarithmic scale over the process' daily output. I.e., for *Laser beam* from zero to 5,040, since its capacity per shift is 1,680 parts, for *Infeed* from zero to 37,800, and for *Progress dedicated tool* form zero to 63,000. Because the curves of the marginal costs increase in steps, given by the model, their regression lines are added. Four things can be seen in this chart:

1. *Progress dedicated tool* is more volume flexible than *Infeed* and *Laser beam*. This is expressed by its flatter average cost curve and the less steep slope of the marginal costs.

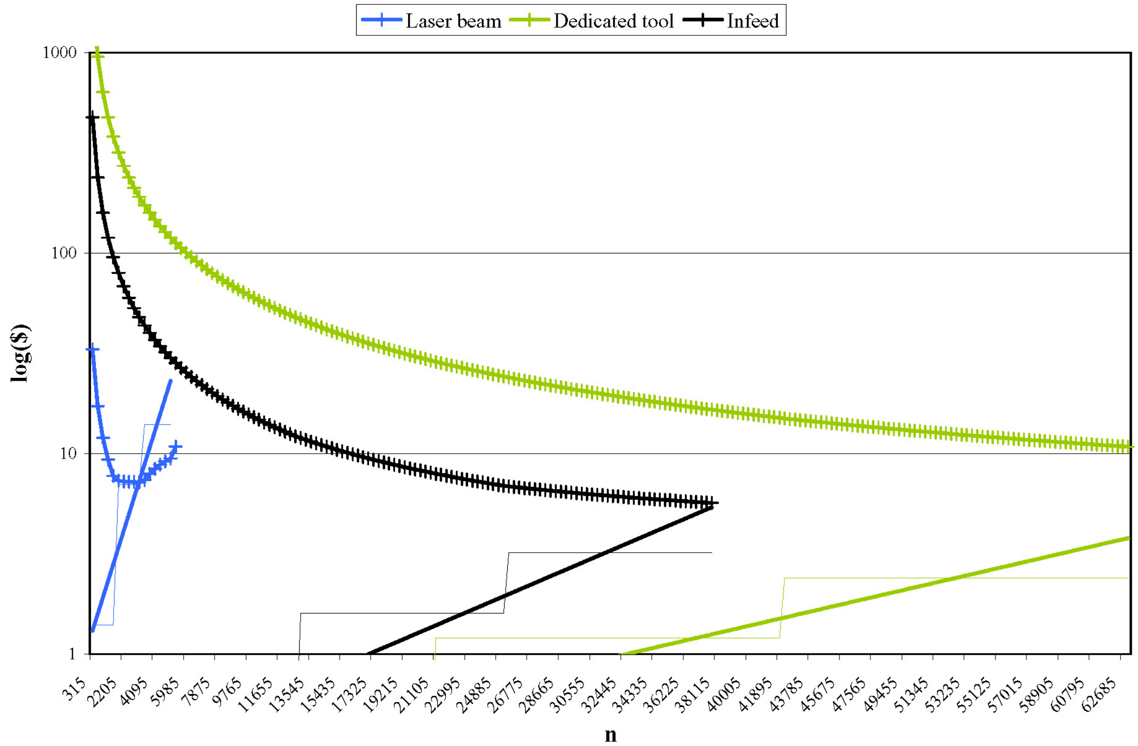

Figure B-7: Cost curves for *Laser beam*, *Infeed*, and *Progress dedicated tool*

2. The lowest average costs are at the intersection of the average and the marginal cost curves. Notice, that for that analysis, not the regression line of the marginal cost, but the original run of the curve must be observed. Therefore, the optimal production output it as that point too. Since the marginal costs of *Infeed* and *Progress dedicated tool* do not intersect their corresponding average cost curves, it may be concluded that for these processes the variable costs were assumed too low in relation to their fixed costs. I.e., those processes cannot tap the full potential within their capacity.

3. The optimal output volume of *Progress dedicated tool* is at a higher level than that of *Infeed* and *Laser beam*.

4. The average costs at the optimal production volume for *Infeed* are lower than those of *Laser beam* at its optimal production rate. The minimum of the average costs for *Progress dedicated tool* cannot be seen in this chart, but they might be higher than the minimal costs of *Infeed*.

For answering the question of the profitability limits of each process, the cost curves must be set in relation to sales prices curves. The difference between the sales price and the average cost curve gives the profit. If the cost curve is above the sales price, the process is no longer in the profitable range.

Finally, a connection from Figure B-7 to Mills' cost function is made. Since with Mills' formula the optimal production volume for a given process can be determined, the quadratic cost function is approximated to the curves above, using the method of minimum square deviation. Thus, the parameters α, β, and δ can be defined. The optimal production volume then is given as $\sqrt{2\alpha\delta}$. See Table B.3 for the results of this approximation. The approximation of *Laser beam* is not very good, probably

	Laser beam	Infeed	Prog. Ded. Tool
α	10,000	150,000	600,000
β	6.93	0	0
δ	1,073	4,610	24,795
$\sqrt{2\alpha\delta}$	4,632	37,189	172,493

Table B.3: Optimal production volume according to Mills' cost function for *Laser beam*, *Infeed*, and *Progress dedicated tool*

due to too few reading points. Therefore, the optimal output volume for this process as given in Table B.3 is higher then the one that can be seen in Figure B-7. The congruence of the results for *Infeed* is promising for further research about this cost function. The outcome for *Progress dedicated tool* can not be verified, but might be in an acceptable range.

Although the process parameters in the lever problem are assumed and subject to uncertainty, the tendencies in the chart are obvious. So, with this analysis, either the concepts are 'proven' by reconstructing them with 'real' data, or the other way around, the process parameters assumed for the lever problem are hereby validated to be in an acceptable range.

Appendix C

Questionnaire and Answers

C.1 Questionnaire

The questionnaire shown below was used for the visits of firms (see also section 2.5). It was sent to the firms in advance of the visits so that the representatives of the firms had an idea in what the discussion is about and could prepare themselves. The original questionnaire was written in German, but has been translated for this report.

The questionnaire is organized in three parts. Part A contains general questions about the firm, part B asks for metal forming relevant markets, products and production facilities, and part C deals with the organization of the production processes. The idea is to gather some data in parts A and B for the case study (Lever Problem). The practical insight from a firm to the questions in part C should help to answer the key questions of the thesis.

Part A: Questions about the firm

A1) Scope of business: What is the activity of the firm? In which branch of trade does the firm operate?

A2) Organization of the firm: What is the organizational structure of the firm? How many employees does the firm have? Can you describe the corporate culture?

A3) Key figures: Can you give numbers for business volume, EBIT, total assets, etc.?

A4) Market: Can do describe the market environment? How many competitors do you have and how powerful are they? What is your own market share?

Part B: Questions about the division 'components manufacturing by metal forming processes'

B1) Key figures: What is the business volume for this division? How many people are employed here? What is the annual capital expenditure for infrastructure in the fabrication?

B2) Market: How big is your market share? Are you competing in an attractive market environment? Is there severe competition? In which price segment are you located? What is your volume segment?

B3) Customer: In which branches of trade are your customers operating? Can you give an ABC analysis of your customers, are there few main customers or are sales rather evenly distributed over most customers? What is the market position of your customers in their branches? Do your customers need your products for product platforms or reusable modules?

B4) Cooperation with customers: Do you have long term contracts with your customers? Are you involved in development projects of your customers? Which degree of flexibility is demanded from your customers?

B5) Machinery: How modern are your fabrication facilities? What is the automatization level of your machinery? What is the degree of flexibility of the machinery as a whole? Which degree of flexibility do individual machines have?

B6) Assortment of products: Please provide some data about some interesting (matching the topic of the thesis) products: Can you tell the annual sale volume, the proportion to total sale, the level of product and process complexity, manufacturing costs, degree of flexibility in the choice of means of production, annual fluctuation in demand, range of geometric bandwidth, number of variants of this part?

Part C: Questions about the production process

C1) State-of-the-art: What is the current state-of-the-art in flexible component manufacturing systems? Can new processes (e.g. hydro-forming) increase flexibility without taking a major loss along other dimensions (e.g. part costs, tolerances)?

C2) Best practice: What are best practices of competitors in the same industry and in related industries regarding flexible component manufacturing systems?

C3) Strategies: What are different strategies for achieving flexibility in the capacity of a manufacturing system (separate, parallel lines that can be activated as needed, adding shifts, outsourcing during demand peaks...)?

C4) Manufacturing costs: How do the fixed, variable and total per-part costs change as different manufacturing processes are scaled up in terms of the number of units produced? Where are the crossover points between metal forming and high speed machining processes as a function of the number of units?

C5) Influence capability of design: Which processes are more flexible than others in terms of part geometries and specifications (surface roughness, thickness distributions, pre-stress levels)? How can this flexibility be quantified?

C6) Modern concepts: Where and how can modern concepts such as virtual production planning and simulation or modular tooling be leveraged to increase flexibility?

C7) Guidance to reach flexibility: Given stochastic estimates of future demand in terms of part geometries and number of units to be produced, can you conceive of a scheme to optimize the strategy for and architecture of flexible manufacturing systems? Do you use real options to quantify the value of flexibility?

C8) Advantages and disadvantages: What are the quantifiable benefits and penalties when flexibility is embedded?

C.2 Answers

In this section the firms' answers are given in note form to each question where an answer is available. See also Section 2.5 for a summary of the answers. Even though the firms gave more answers, not all are published here due to non-disclosure agreements.

C.2.1 Firm A

A1 Machines, apparatus engineering, production of complex parts with long lifetime, small subcontractor to several firms, family enterprise. Manufacturer of scissors for cutting trees, metallic parts, but neither for automotive nor for aerospace industries, parts for aerospace industry made out of carbon fiber and not produced by forming processes, bedsprings produced by forming technology, but made out of carbon fiber

A2 20 employees, loyal employees, good team

A4 Huge fluctuations in quantities ordered, several projects

B3 Few key accounts, several smaller contracts

B5 Old machinery, low automation level

B6 Parts in quantities of 5000 to 50000 in the whole life cycle, most of of them in stainless steel

C1 Traditional forming process adapted to be able to form modern materials such as carbon fibers

C2 Old machinery, specific tools

C3 Triangle 'Price – Process – Quality' must be balanced

C6 No, too expensive

C8 Annual working time to enable volume flexibility, good and loyal employees

C.2.2 Firm B

A1 Military and civil aerospace industry, astronautical industry

A2 2500 employees in aerospace division

A3 Group: net sales: 1006 mill CHF, EBIT: 63.5 mill CHF, net profit: 44 mill CHF, total assets: 528 mill CHF

B1 26 employees, net sales: 3 mill CHF

B2 Leader in Switzerland, marginal in Europe, middle price segment

B5 Several presses, bending machines at different automation and flexibility levels

B6 100 to 6000 parts per year per product, high fluctuations

C1 Rather old machinery, latest investments in high-speed machining

C2 When ever possible: Hydro-forming

C3 Additional shifts to increase capacity

C4 Sometimes influence on part design during offer phase, after that difficult due to validation process

C6 Virtual Production Planning once tried, but insufficient results

C7 Multi functional and modular machinery, lot size 1

C8 Difficult to teach the employees flexibility, no warehousing

C.2.3 Firm C

A1 Automobile industry: steering columns, rings for ABS systems, parts for lamps, windscreen wipers; Caps for aerosol cans; Electrostatic shields for mobile phones; further industrial applications

A2 500 employees, good corporate culture

A3 Net sales: 100 mill CHF, EBIT: 2-3%

A4 Just big enough to be accepted as TIER 1 or TIER 2 supplier in automotive industry, Competitors mainly in European Community

B1 350 employees, 1-2 mill CHF investment per year

B3 Few key accounts, several further customers

B4 Dependent on customer, no supply chain; Product is more important than partnership

B5 Rather modern machinery, but ‘zoo’,i.e., one of each type, low utilization ratio, high flexibility with presses

B6 From heavily built to very fragile parts, classification difficult; Predictions for future sales very good

C1 Stamping, deep drawing as processes, output rates from 30 to 80 parts per minute for larger products to 250 to 300 parts per minute for smaller products; Hydro-forming is too slow, only usable for prototypes

C3 1 tool 1 press 1 product - otherwise review and new validation, therefore flexibility limited

C5 Tight cooperation during product and process development

C6 FEM simulation is OK, process simulation too complex to interpret the results

C7 Feasibility is major concern, not flexibility, thus little experience with flexibility

C8 Annual working time model, challenging to run

Appendix D

Simulation Code

For the simulation mentioned in chapter 3.2 the software package Microsoft Excel is used and the program for the simulation was written in the programming language Visual Basic. In this section the whole program code is shown. For better understanding, it is recommended to have a look at the original Microsoft Excel file which can be found on the CD (see Appendix H) at the end of this report.

The routine consists of 10 procedures which are run in the sequence as shown in figure D-1. It has to be said that the code for this simulation has grown by using it. An underscore '_' at the end of a line in the code is used as a connector between two lines. So the initiated command will be continued on the next line.

Parameters of the market scenarios are entered in the spreadsheet *Market*. In the sheet named *Process* all data concerning the process scenarios are available. The last table with input data is named *Model*, it contains general data like numbers of workdays per year and numbers of shifts, etc.

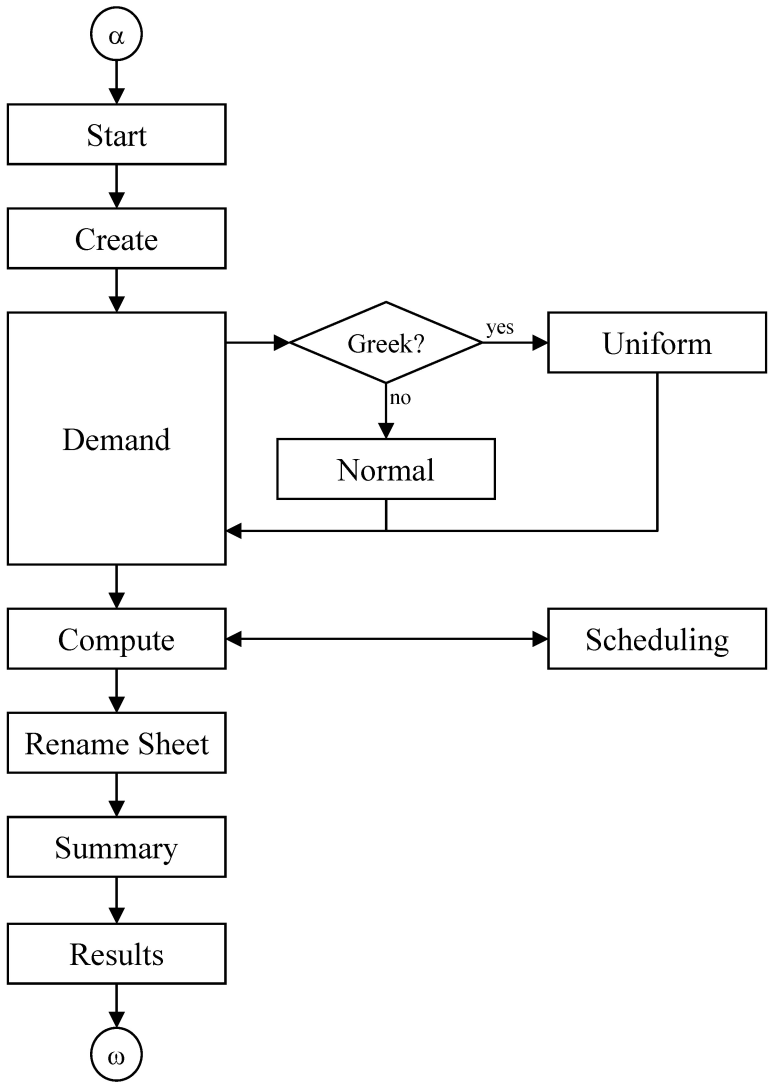

Figure D-1: Program sequence

After clicking the *Run Simulation* button at the spreadsheet *Simulation* the procedure *Start*, see Figure D-2, is run. It acts as main procedure and controls all the other procedures.

```
Private Sub Start_Click()
On Error GoTo Err_Start_Click

Runs = ActiveSheet.Cells(7, 2)
For r = 1 To Runs 'Number of runs

Application.ScreenUpdating = False
Create Row, Col
Demand Col
Compute Row, Col, i
RenameSheet
Summary Row, Col, i
Results


Application.ScreenUpdating = True
Next r
MsgBox "Finished"

Exit_Err_Start_Click:
    Exit Sub

Err_Start_Click:
    MsgBox Err.Description
    Resume Exit_Err_Start_Click

End Sub
```

Figure D-2: Sub *Start*

The sub procedure *Create*, see figures D-3 and D-4, creates a new spreadsheet with the name *Sim* and inserts start values needed for the calculation.

```
Public Sub Create(Row, Col)
On Error GoTo Err_Create


Sheets("Master").Copy After:=Sheets(Sheets.Count)
ActiveSheet.Name = "Sim"

ActiveSheet.Cells(1, 5) = Worksheets("Simulation").Cells(3, 2)
ActiveSheet.Cells(2, 5) = Worksheets("Simulation").Cells(5, 2)

Select Case ActiveSheet.Cells(2, 5) 'Determine the prodction case
    Case "Progress dedicated tool"
        Row = 1
    Case "Progress adjustable tool"
        Row = 21
    Case "Laser beam"
        Row = 41
    Case "Punching"
        Row = 61
    Case "Milling"
        Row = 81
    Case "Infeed"
        Row = 101
End Select

ActiveSheet.Cells(4, 5) = 1 / (60 * Worksheets("Process").Cells(Row + 2, 2)) 'Production time per part
ActiveSheet.Cells(5, 5) = Worksheets("Model").Cells(10, 2) * Worksheets("Model").Cells(11, 2) _
    / ActiveSheet.Cells(4, 5) 'Capacity per day
ActiveSheet.Cells(6, 5) = Worksheets("Process").Cells(Row + 3, 2) / Worksheets("Process"). _
    Cells(Row + 4, 2) / Worksheets("Model").Cells(9, 2) / Worksheets("Model").Cells(10, 2) _
    / Worksheets("Model").Cells(11, 2) 'Machine cost per hour
ActiveSheet.Cells(7, 5) = Worksheets("Process").Cells(Row + 11, 2) * (ActiveSheet.Cells(6, 5) _
    + Worksheets("Process").Cells(Row + 12, 2)) 'Switching costs
ActiveSheet.Cells(9, 5) = ActiveSheet.Cells(6, 5) * ActiveSheet.Cells(4, 5) 'Machine costs per part
ActiveSheet.Cells(10, 5) = ActiveSheet.Cells(4, 5) * Worksheets("Process").Cells(Row + 12, 2) _
    'Work and other variable costs per part
ActiveSheet.Cells(11, 5) = ActiveSheet.Cells(9, 5) + ActiveSheet.Cells(10, 5) _
    'Time depended costs per part

Select Case ActiveSheet.Cells(1, 5) 'Determine the market case
    Case "2003"
        Col = 3
    Case "Status Quo"
        Col = 4
    Case "Plus D"
        Col = 5
    Case "Greek"
        Col = 6
End Select
```

Figure D-3: Sub *Create* part 1 of 2

```
For i = 1 To 4 'Costs common tool per part
    ActiveSheet.Cells(13, i + 4) = Worksheets("Process").Cells(Row + 5, Col) / _
        Worksheets("Process").Cells(Row + 10, 2)
Next i
For i = 1 To 4 'Costs dedicated tool per part
    ActiveSheet.Cells(14, i + 4) = Worksheets("Process").Cells(Row + 5 + i, Col) / _
        Worksheets("Process").Cells(Row + 10, 2)
Next i
For i = 1 To 4 'Material costs per part
    ActiveSheet.Cells(15, i + 4) = Worksheets("Model").Cells(13, 2) * _
        Worksheets("Market").Cells(i + 41, Col + 9) / Worksheets("Process").Cells(Row + 13, 2)
Next i
For i = 1 To 4 'Quantity depended costs per part
    ActiveSheet.Cells(16, i + 4) = ActiveSheet.Cells(13, i + 4) + ActiveSheet.Cells(14, i + 4) _
        + ActiveSheet.Cells(15, i + 4)
Next i

If ((Col = 4 Or Col = 5) = True) And Row = 1 Then 'Account Tool if actual tool can be used next year
    For i = 1 To 4
        ActiveSheet.Cells(22, 21 + i) = Worksheets("Process").Cells(Row + 5 + i, Col) _
            * (1 - Worksheets("Market").Cells(30 + i, 12) / Worksheets("Process").Cells(Row + 10, 2)) _
            'dedicated tools
    Next i
        ActiveSheet.Cells(22, 26) = Worksheets("Process").Cells(Row + 5, Col) 'common tools
Else 'Account Tool if new tools must be made for next years
    For i = 1 To 4
        ActiveSheet.Cells(22, 21 + i) = Worksheets("Process").Cells(Row + 5 + i, Col) 'dedicated tools
        ActiveSheet.Cells(22, 26) = Worksheets("Process").Cells(Row + 5, Col) 'common tools
    Next i
End If

For j = 1 To 4 'Set Stock and Overdue
    ActiveSheet.Cells(22, 30 + j) = Worksheets("Model").Cells(20, 1 + j) 'Stock
    ActiveSheet.Cells(22, 34 + j) = Worksheets("Model").Cells(21, 1 + j) 'Overdue
Next j


For i = 1 To Worksheets("Model").Cells(9, 2) 'Enumerate Workdays
    ActiveSheet.Cells(22 + i, 1) = i
Next i

Exit_Create:
    Exit Sub
Err_Create:
    MsgBox Err.Description
    Resume Exit_Create

End Sub
```

Figure D-4: Sub *Create* part 2 of 2

The next sub procedure *Demand* (Figure D-5) together with its two sub functions *Uniform* (Figure D-6) and *Normal* (Figure D-7) is the actual simulation and therefore the 'core' part. In the first step in *Demand*, it has to be distinguished whether the demand is normal (in case of market scenarios *Status Quo* and *Plus D*) or uniformly (in the case of market scenario *Greek*) distributed. Then, a randomly chosen number simulates the demand of a part at one day.

```
Public Sub Demand(Col)
On Error GoTo Err_Demand
Dim mv As Variant

If Col = 6 Then 'If Market scenario 'Greek' then uniform distribution
    up = 500000 / Worksheets("Model").Cells(9, 2)
    low = 50000 / Worksheets("Model").Cells(9, 2)
    For j = 1 To 3
        For i = 1 To Worksheets("Model").Cells(9, 2)
            ActiveSheet.Cells(i + 22, j + 1) = Uniform(up, low)
        Next i
    Next j
ElseIf Col = 5 Then 'If Market Scenario 'Plus D' then fill 4 rows
    std = Worksheets("Model").Cells(15, 2)
    For j = 1 To 4
            mv = Worksheets("Market").Cells(30 + j, Col + 9) / _
            Worksheets("Model").Cells(9, 2) 'Mean Value
        For i = 1 To Worksheets("Model").Cells(9, 2)
            ActiveSheet.Cells(i + 22, j + 1) = Normal(mv, std)
        Next i
    Next j
Else 'In all other cases mean normal distribution
    std = Worksheets("Model").Cells(15, 2)
    For j = 1 To 3
            mv = Worksheets("Market").Cells(30 + j, Col + 9) / _
            Worksheets("Model").Cells(9, 2) 'Mean Value
        For i = 1 To Worksheets("Model").Cells(9, 2)
            ActiveSheet.Cells(i + 22, j + 1) = Normal(mv, std)
        Next i
    Next j
End If

Exit_Demand:
    Exit Sub
Err_Demand:
    MsgBox Err.Description
    Resume Exit_Demand

End Sub
```

Figure D-5: Sub *Demand*

```
Public Function Uniform(up, low)
On Error GoTo Err_Uniform

Uniform = Int((up - low + 1) * Rnd + low)

Exit_Uniform:
    Exit Function
Err_Uniform:
    MsgBox Err.Description
    Resume Exit_Uniform

End Function
```

Figure D-6: Function *Uniform*

```
Public Function Normal(mv, std)
On Error GoTo Err_Normal

strech = 2.667 'factor for setting the ~2Sigma range

up = Int(((mv + strech * std) - mv + 1) * Rnd + mv)
low = Int((mv - (mv - strech * std) + 1) * Rnd + (mv - strech * std))

Normal = Int((up - low + 1) * Rnd + low)

If Normal < 0 Then
    Normal = 0
End If

Exit_Normal:
    Exit Function
Err_Normal:
    MsgBox Err.Description
    Resume Exit_Normal

End Function
```

Figure D-7: Function *Normal*

The following sub procedure *Compute* (see figures D-8, D-9, and D-10) calculates all needed data. For further details see section 3.2.3. The function *Scheduling* (Figure D-11) makes the decision in which order the parts should be produced to optimize the firms earnings.

```
Public Sub Compute(Row, Col, i)
On Error GoTo Err_Compute

ManufcostA = 0 'Set Manufacturing cost start value
ManufcostB = 0
ManufcostC = 0
ManufcostD = 0

For i = 1 To Worksheets("Model").Cells(9, 2)
Totalcost = 0 'Set total cost start value
Totalrevenue = 0 'Set total revenue start value
Totalearning = 0 'Set total earning start value

    For j = 1 To 4 'Target production
        ActiveSheet.Cells(22 + i, 5 + j) = Application.WorksheetFunction.Max(ActiveSheet.Cells _
            (22 + i, 1 + j) - ActiveSheet.Cells(21 + i, 30 + j) + ActiveSheet.Cells(21 + i, 34 + j), 0)
    Next j

    Scheduling i, Col 'Actual Production

    For j = 1 To 4 'Switching costs
        If ActiveSheet.Cells(22 + i, 9 + j) = 0 Then
            ActiveSheet.Cells(22 + i, 13 + j) = 0
        Else
            ActiveSheet.Cells(22 + i, 13 + j) = ActiveSheet.Cells(7, 5) / _
                ActiveSheet.Cells(22 + i, 9 + j)
        End If
    Next j
    For j = 1 To 4 'Manufacturing costs part
        ActiveSheet.Cells(22 + i, 17 + j) = (ActiveSheet.Cells(11, 5) + ActiveSheet.Cells(16, 4 + j) _
            + ActiveSheet.Cells(22 + i, 13 + j)) * (1 + Worksheets("Model").Cells(12, 2)) / _
            Worksheets("Process").Cells(Row + 14, 2) '... *overhead /useful parts
    Next j
    ManufcostA = ManufcostA + ActiveSheet.Cells(22 + i, 18) _
        'for the calculation of the average manufacturing cost for stock keeping
    ManufcostB = ManufcostB + ActiveSheet.Cells(22 + i, 19)
    ManufcostC = ManufcostC + ActiveSheet.Cells(22 + i, 20)
    ManufcostD = ManufcostD + ActiveSheet.Cells(22 + i, 21)

    For j = 1 To 4 'Account Tool dedicated tools
        If ActiveSheet.Cells(21 + i, 21 + j) > 0 Then
            ActiveSheet.Cells(22 + i, 21 + j) = ActiveSheet.Cells(21 + i, 21 + j) _
                - ActiveSheet.Cells(22 + i, 9 + j) * ActiveSheet.Cells(14, 4 + j)
        Else
            ActiveSheet.Cells(22 + i, 21 + j) = Worksheets("Process").Cells(Row + 5 + j, Col) _
                'for day 1
        End If
    Next j
```

Figure D-8: Sub *Compute* part 1 of 3

```
If ActiveSheet.Cells(21 + i, 26) > 0 Then 'Account Tool common tools
    ActiveSheet.Cells(22 + i, 26) = ActiveSheet.Cells(21 + i, 26) - (ActiveSheet.Cells _
        (22 + i, 10) * ActiveSheet.Cells(13, 5) + ActiveSheet.Cells(22 + i, 11) * _
        ActiveSheet.Cells(13, 6) + ActiveSheet.Cells(22 + i, 12) * ActiveSheet.Cells(14, 7) + _
        ActiveSheet.Cells(22 + i, 13) * ActiveSheet.Cells(13, 8))
Else
    ActiveSheet.Cells(22 + i, 26) = Worksheets("Process").Cells(Row + 5, Col) 'for day 1
End If
For j = 1 To 4 'Sale
    ActiveSheet.Cells(22 + i, 26 + j) = Application.WorksheetFunction.Min(ActiveSheet.Cells _
        (22 + i, 1 + j) + ActiveSheet.Cells(21 + i, 34 + j), ActiveSheet.Cells(22 + i, 9 + j) + _
        ActiveSheet.Cells(21 + i, 30 + j))
Next j
For j = 1 To 4 'Stock
    ActiveSheet.Cells(22 + i, 30 + j) = ActiveSheet.Cells(21 + i, 30 + j) + _
        ActiveSheet.Cells(22 + i, 9 + j) - ActiveSheet.Cells(22 + i, 26 + j)
Next j
For j = 1 To 4 'Overdue
    ActiveSheet.Cells(22 + i, 34 + j) = ActiveSheet.Cells(21 + i, 34 + j) + _
        ActiveSheet.Cells(22 + i, 1 + j) - ActiveSheet.Cells(22 + i, 26 + j)
Next j
For j = 1 To 4 'Manufacturing costs cumulated
    ActiveSheet.Cells(22 + i, 38 + j) = ActiveSheet.Cells(22 + i, 9 + j) * _
        ActiveSheet.Cells(22 + i, 17 + j)
Next j
'Costs for stock keeping
ActiveSheet.Cells(22 + i, 43) = ActiveSheet.Cells(22 + i, 31) * Worksheets("Model").Cells(3, 2) _
    * ManufcostA / i / Worksheets("Model").Cells(9, 2) _
    'number of parts in stock * stock costs * average manufacturing costs (up to date)/ _
    workdays per year
ActiveSheet.Cells(22 + i, 44) = ActiveSheet.Cells(22 + i, 32) * Worksheets("Model").Cells(3, 2) _
    * ManufcostB / i / Worksheets("Model").Cells(9, 2)
ActiveSheet.Cells(22 + i, 45) = ActiveSheet.Cells(22 + i, 33) * Worksheets("Model").Cells(3, 2) _
    * ManufcostC / i / Worksheets("Model").Cells(9, 2)
ActiveSheet.Cells(22 + i, 46) = ActiveSheet.Cells(22 + i, 34) * Worksheets("Model").Cells(3, 2) _
    * ManufcostD / i / Worksheets("Model").Cells(9, 2)

For j = 1 To 4 'Overdue costs
    If ActiveSheet.Cells(21 + i, 34 + j) < ActiveSheet.Cells(22 + i, 34 + j) Then
        ActiveSheet.Cells(22 + i, 46 + j) = (ActiveSheet.Cells(22 + i, 34 + j) - _
            ActiveSheet.Cells(21 + i, 34 + j)) * Worksheets("Model").Cells(5, 2) * _
            Worksheets("Market").Cells(36 + j, Col + 9)
    Else
        ActiveSheet.Cells(22 + i, 46 + j) = 0
    End If
Next j
For j = 1 To 4 'Total costs
    ActiveSheet.Cells(22 + i, 50 + j) = ActiveSheet.Cells(22 + i, 38 + j) + _
        ActiveSheet.Cells(22 + i, 42 + j) + ActiveSheet.Cells(22 + i, 46 + j)
    Totalcost = Totalcost + ActiveSheet.Cells(22 + i, 50 + j)
Next j
```

Figure D-9: Sub *Compute* part 2 of 3

```
    ActiveSheet.Cells(22 + i, 55) = Totalcost 'Total(total cost)
    For j = 1 To 4 'Total revenue
        ActiveSheet.Cells(22 + i, 55 + j) = ActiveSheet.Cells(22 + i, 26 + j) * _
            Worksheets("Market").Cells(36 + j, Col + 9)
        Totalrevenue = Totalrevenue + ActiveSheet.Cells(22 + i, 55 + j)
    Next j
    ActiveSheet.Cells(22 + i, 60) = Totalrevenue 'Total(total revenue)
    For j = 1 To 4 'Earnings
        ActiveSheet.Cells(22 + i, 60 + j) = ActiveSheet.Cells(22 + i, 55 + j) - _
            ActiveSheet.Cells(22 + i, 50 + j)
        Totalearning = Totalearning + ActiveSheet.Cells(22 + i, 60 + j)
    Next j
    ActiveSheet.Cells(22 + i, 65) = Totalearning

    If i Mod 3 = 0 Then
        ActiveSheet.Range(ActiveSheet.Cells(22 + i, 1), ActiveSheet.Cells(22 + i, 65)) _
            .Interior.ColorIndex = 35
    End If
Next i

ActiveSheet.Cells(18, 5) = ManufcostA / Worksheets("Model").Cells(9, 2) 'Average manufacturing costs
ActiveSheet.Cells(18, 6) = ManufcostB / Worksheets("Model").Cells(9, 2)
ActiveSheet.Cells(18, 7) = ManufcostC / Worksheets("Model").Cells(9, 2)
ActiveSheet.Cells(18, 8) = ManufcostD / Worksheets("Model").Cells(9, 2)

ActiveSheet.Cells(22 + i, 1) = "Total"
For s = 2 To 65 'all columns
    total = 0
    For z = 23 To (21 + i)
        total = total + ActiveSheet.Cells(z, s)
    Next z
    ActiveSheet.Cells(22 + i, s) = total
Next s

ActiveSheet.Range(ActiveSheet.Cells(22 + i, 1), ActiveSheet.Cells(22 + i, 65)).Select _
        'Set Borders to 'total' row
    Selection.Borders(xlDiagonalDown).LineStyle = xlNone
    Selection.Borders(xlDiagonalUp).LineStyle = xlNone
    Selection.Borders(xlEdgeLeft).LineStyle = xlNone
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .Weight = xlThin
        .ColorIndex = xlAutomatic
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .Weight = xlThin
        .ColorIndex = xlAutomatic
    End With
    Selection.Borders(xlEdgeRight).LineStyle = xlNone
    Selection.Borders(xlInsideVertical).LineStyle = xlNone


Exit_Compute:
    Exit Sub
Err_Compute:
    MsgBox Err.Description
    Resume Exit_Compute

End Sub
```

Figure D-10: Sub *Compute* part 3 of 3

```
Public Sub Scheduling(i, Col)
On Error GoTo Err_Scheduling

Dim Pos(2, 4) As Variant 'define 2x4 matrix

For j = 1 To 4 'Fill Margins (last period) of Lever A to D in the upper row of the matrix Pos
    Pos(1, j) = Worksheets("Market").Cells(36 + j, Col + 9) - ActiveSheet.Cells(21 + i, 17 + j)
Next j

For j = 1 To 4 'initialize order
    Pos(2, j) = j
Next j


z = 1 'counter how many switches were made
Do While z > 0 'Bubble sort algorithm
    z = 0
    For j = 1 To 3
        If Pos(1, j + 1) > Pos(1, j) Then 'if right element is bigger than left one, switch elements
            D = Pos(1, j)
            Pos(1, j) = Pos(1, j + 1)
            Pos(1, j + 1) = D
            D = Pos(2, j)
            Pos(2, j) = Pos(2, j + 1)
            Pos(2, j + 1) = D
            z = z + 1
        End If
    Next j
Loop

For j = 1 To 4
need = ActiveSheet.Cells(22 + i, 5 + Pos(2, j))
cap = Application.WorksheetFunction.Max(0, ActiveSheet.Cells(5, 5) - (ActiveSheet.Cells(22 + i, 10) + _
    ActiveSheet.Cells(22 + i, 11) + ActiveSheet.Cells(22 + i, 12) + ActiveSheet.Cells(22 + i, 13)))
If cap > need Then
    volume = need
Else
    volume = cap
End If
ActiveSheet.Cells(22 + i, 9 + Pos(2, j)) = volume
Next j

Exit_Scheduling:
    Exit Sub
Err_Scheduling:
    MsgBox Err.Description
    Resume Exit_Scheduling

End Sub
```

Figure D-11: Sub *Scheduling*

After finishing calculating, the spreadsheet *Sim* will be renamed to a unique name composed of the month, date, hour, minute, and second of the simulation run. Therefore the procedure *Rename Sheet* (see Figure D-12) is needed.

```
Public Sub RenameSheet()
On Error GoTo Err_RenameSheet

Worksheets("Sim").Activate
ActiveSheet.Name = Month(Date) & "-" & Day(Date) & "-" & Hour(Now) & "-" & Minute(Now) & "-" _
    & Second(Now)

Exit_RenameSheet:
    Exit Sub
Err_RenameSheet:
    MsgBox Err.Description
    Resume Exit_RenameSheet

End Sub
```

Figure D-12: Sub *Rename Sheet*

To get a summary of all results and input parameters, the procedure *Summary* (figures D-13 and D-14) collects all relevant data and copies them to the head of the simulation sheet.

```
Public Sub Summary(Row, Col, i)
On Error GoTo Err_Summary

'Fills the 'head' of the result sheet

ActiveSheet.Cells(1, 14) = ActiveSheet.Name 'Run number
ActiveSheet.Cells(3, 14) = Worksheets("Model").Cells(9, 2) 'Workdays per year
ActiveSheet.Cells(4, 14) = Worksheets("Model").Cells(10, 2) 'Shifts per day
ActiveSheet.Cells(5, 14) = Worksheets("Model").Cells(11, 2) 'Workhours per day
ActiveSheet.Cells(6, 14) = Worksheets("Model").Cells(15, 2) 'Standard deviation of demand (in parts)
ActiveSheet.Cells(7, 14) = Worksheets("Model").Cells(12, 2) 'Overhead
ActiveSheet.Cells(8, 14) = Worksheets("Model").Cells(13, 2) 'Material unit price
ActiveSheet.Cells(10, 14) = Worksheets("Model").Cells(3, 2) 'Stock keeping costs
ActiveSheet.Cells(11, 14) = Worksheets("Model").Cells(5, 2) 'Overdue costs

ActiveSheet.Cells(15, 14) = Worksheets("Process").Cells(Row + 5, Col) 'Common tool cost
For j = 1 To 4 'dedicated tool cost
    ActiveSheet.Cells(17, 13 + j) = Worksheets("Process").Cells(Row + 5 + j, Col)
Next j
ActiveSheet.Cells(14, 14) = Worksheets("Process").Cells(Row + 10, 2) 'tool lifetime
ActiveSheet.Cells(12, 14) = Worksheets("Process").Cells(Row + 3, 2) 'Machine cost
ActiveSheet.Cells(13, 14) = Worksheets("Process").Cells(Row + 4, 2) 'Machine lifetime

ActiveSheet.Cells(1, 22) = Worksheets("Process").Cells(Row + 2, 2) 'Outputrate
ActiveSheet.Cells(2, 22) = Worksheets("Process").Cells(Row + 11, 2) 'Switching time
ActiveSheet.Cells(3, 22) = Worksheets("Process").Cells(Row + 12, 2) 'Variable costs per hour
ActiveSheet.Cells(4, 22) = Worksheets("Process").Cells(Row + 13, 2) 'Raw material utilization
ActiveSheet.Cells(5, 22) = Worksheets("Process").Cells(Row + 14, 2) 'Useful parts

For j = 1 To 4 'Part lengths
    ActiveSheet.Cells(7, 21 + j) = Worksheets("Market").Cells(41 + j, Col + 9)
Next j
For j = 1 To 4 'Sale price
    ActiveSheet.Cells(8, 21 + j) = Worksheets("Market").Cells(36 + j, Col + 9)
Next j
For j = 1 To 4 'Demand
    ActiveSheet.Cells(9, 21 + j) = ActiveSheet.Cells(22 + i, 1 + j)
Next j
For j = 1 To 4 'Average daily demand
    ActiveSheet.Cells(10, 21 + j) = ActiveSheet.Cells(9, 21 + j) / ActiveSheet.Cells(3, 14)
Next j
For j = 1 To 4 'Production
    ActiveSheet.Cells(11, 21 + j) = ActiveSheet.Cells(22 + i, 9 + j)
Next j
prodtime = 0 'set variable prodtime
For j = 1 To 4 'total production time
    ActiveSheet.Cells(12, 21 + j) = ActiveSheet.Cells(11, 21 + j) * ActiveSheet.Cells(4, 5)
    prodtime = prodtime + ActiveSheet.Cells(12, 21 + j)
Next j
ActiveSheet.Cells(13, 22) = prodtime / (ActiveSheet.Cells(3, 14) * ActiveSheet.Cells(4, 14) * _
    ActiveSheet.Cells(5, 14)) 'Machine utilization
```

Figure D-13: Sub *Summary* part 1 of 2

```
For j = 1 To 4 'Min daily demand
    ActiveSheet.Cells(15, 21 + j) = Application.WorksheetFunction.Min(ActiveSheet.Range _
        (ActiveSheet.Cells(23, 1 + j), ActiveSheet.Cells(21 + i, 1 + j)))
Next j
For j = 1 To 4 'Max daily demand
ActiveSheet.Cells(16, 21 + j) = Application.WorksheetFunction.Max(ActiveSheet.Range _
        (ActiveSheet.Cells(23, 1 + j), ActiveSheet.Cells(21 + i, 1 + j)))
Next j

For j = 1 To 5 'Revenue
    ActiveSheet.Cells(2, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 55 + j)
Next j
For j = 1 To 5 'Costs
    ActiveSheet.Cells(3, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 50 + j)
Next j
For j = 1 To 5 'Earnings
    ActiveSheet.Cells(4, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 60 + j)
Next j
For j = 1 To 4 'Manufacturing costs
    ActiveSheet.Cells(6, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 38 + j)
Next j
ActiveSheet.Cells(6, 37) = Application.WorksheetFunction.Sum( _
    ActiveSheet.Range(ActiveSheet.Cells(6, 29), ActiveSheet.Cells(6, 35))) 'Total manufacturing costs
For j = 1 To 4 'Stock costs
    ActiveSheet.Cells(7, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 42 + j)
Next j
ActiveSheet.Cells(7, 37) = Application.WorksheetFunction.Sum( _
    ActiveSheet.Range(ActiveSheet.Cells(7, 29), ActiveSheet.Cells(7, 35))) 'Total stock costs
For j = 1 To 5 'Overdue costs
    ActiveSheet.Cells(8, 27 + 2 * j) = ActiveSheet.Cells(22 + i, 46 + j)
Next j
ActiveSheet.Cells(8, 37) = Application.WorksheetFunction.Sum( _
    ActiveSheet.Range(ActiveSheet.Cells(8, 29), ActiveSheet.Cells(8, 35))) 'Total overdue costs
For j = 1 To 5 'Account Tool
    ActiveSheet.Cells(10, 27 + 2 * j) = ActiveSheet.Cells(21 + i, 21 + j)
Next j
ActiveSheet.Cells(10, 39) = Application.WorksheetFunction.Sum( _
    ActiveSheet.Range(ActiveSheet.Cells(10, 29), ActiveSheet.Cells(10, 37))) 'Total tool account

Application.ScreenUpdating = True
ActiveSheet.Cells(1, 37).Select

Exit_Summary:
    Exit Sub
Err_Summary:
    MsgBox Err.Description
    Resume Exit_Summary

End Sub
```

Figure D-14: Sub *Summary* part 2 of 2

Finally, the most important results are copied into the spreadsheet *Results*, where for each simulation run a new column is opened. This is done by the procedure *Results* as shown in Figure D-15.

```
Public Sub Results()
On Error GoTo Err_Results

Nr = ActiveSheet.Name

Worksheets("Results").Activate
ActiveSheet.Columns(3).Insert Shift:=xlToRight ', CopyOrigin:=xlFormatFromRightOrBelow

ActiveSheet.Cells(1, 3) = Worksheets(Nr).Cells(1, 14) 'Run number
ActiveSheet.Cells(2, 3) = Worksheets(Nr).Cells(1, 5) 'Market Scenario
ActiveSheet.Cells(3, 3) = Worksheets(Nr).Cells(2, 5) 'Process Scenario
ActiveSheet.Cells(4, 3) = Worksheets(Nr).Cells(4, 37) 'Total Earnings
ActiveSheet.Cells(5, 3) = Worksheets(Nr).Cells(10, 39) 'Total Tool Account
ActiveSheet.Cells(6, 3) = Application.WorksheetFunction.Sum(Worksheets(Nr).Range(Worksheets(Nr). _
    Cells(9, 22), Worksheets(Nr).Cells(9, 25))) 'Total Demand

Startsection = 8 'First row distinguished for each lever
Block = 6 'number of rows between same position of each block
For i = 1 To 4
    ActiveSheet.Cells(Startsection + Block * (i - 1), 3) = Worksheets(Nr).Cells(15, 21 + i) _
        'Min day demand
Next i
For i = 1 To 4
    ActiveSheet.Cells(Startsection + Block * (i - 1) + 1, 3) = Worksheets(Nr).Cells(16, 21 + i) _
        'Max day demand
Next i
For i = 1 To 4
    ActiveSheet.Cells(Startsection + Block * (i - 1) + 2, 3) = Worksheets(Nr).Cells(10, 21 + i) _
        'Average day demand
Next i
For i = 1 To 4
    ActiveSheet.Cells(Startsection + Block * (i - 1) + 3, 3) = Worksheets(Nr).Cells(9, 21 + i) _
        'Total demand
Next i
For i = 1 To 4
    ActiveSheet.Cells(Startsection + Block * (i - 1) + 4, 3) = Worksheets(Nr).Cells(11, 21 + i) _
        'Total Production day demand
Next i

ActiveSheet.Cells(32, 3) = Worksheets(Nr).Cells(13, 22) 'Machine utilization

ActiveSheet.Columns(3).EntireColumn.AutoFit
Worksheets(Nr).Activate

Exit_Results:
    Exit Sub
Err_Results:
    MsgBox Err.Description
    Resume Exit_Results

End Sub
```

Figure D-15: Sub *Results*

Appendix E

Sensitivity Analysis

A sensitivity analysis produces information about the robustness of a found solution. The sensitivity analysis is formulated with the input parameters that are used in the simulation of *Status Quo*. *Status Quo* was chosen because, first, it is the most likely market case. And second, its absolute results are closest together, i.e., varying the input parameters in this scenario will have the biggest influence on the results and their ranking. The sensitivity analysis is conducted for all input variables in all process scenarios in *Status Quo*. It is conducted 'ceteris paribus', which means that only a single parameter is changed at once while all other values remain fixed.

The results of the sensitivity analysis for the process scenarios *Infeed* and *Progress dedicated tool* are listed and discussed in Section 3.3.2. The results of the other technology settings as there are *Progress adjustable tool*, *Laser beam*, *Punching*, and *Milling*, as well as the allowed range for general input parameters are shown here.

To determine the window of opportunity of an input parameter, e.g. the output rate of *Progress adjustable tool*, the value of this variable is increased, and decreased, respectively, as long as the ranking of both the earnings and the tool accounts remain the same. In the tables and figures below the results of the analysis are shown.

The tables are read in the way that a parameter can be reduced from its actual value to its minimal value, and neither the ranking of the earnings nor of the tool accounts change. But if the parameter is further decreased another process will take the analyzed process' position in the ranking list. The analogous action is used for the maximum value. A hyphen '-' in the table means that changing a parameter in the indicated direction has no influence on the ranking list and can therefore be set to infinite. An asterisk '*' in the table is set to boundaries at which the ranking of the *tool account* changes. Numbers without an asterisk set limits at which the ranking of the *earnings* changes.

The figure provides the same information as the table, but in addition, shows graphically the possible variation range of the input parameters in percent of the actual value. The actual value is the number written in the middle of bar. While green bars indicate a parameters 'elbowroom' without changing the earnings ranking list, blue bars represent margins at whose exceeding the ranking of the tool accounts will change. Bars that are open at the right end outreach the +300% scale in the chart.

While analyzing these results, one has to bear in mind, that there are positively correlated input parameters such as output rate (the higher the value the better the performance) and negatively correlated ones such as costs for tools (the higher the value the worse the performance).

For examples how to interpret the outcome of the sensitivity analysis see Section 3.3.2.

Progress adjustable tool

Parameter	Min value	Actual value	Max value
Costs common tool C_{Tc}	-	100,000	193,451*
Costs tool A C_{Td_A}	-	75,000	109,904*
Costs tool B C_{Td_B}	-	125,000	169,671*
Costs tool C C_{Td_C}	-	175,000	206,157*
Output rate r_{Output}	18	50	-
Switching time T_S	0.14	0.5	1.1
Variable costs C_{v_H}	-	20	247
Raw material utilization r_{Mat}	78%	100%	-
Useful parts $(1 - r_{Scrap})$	85%	99%	-

Table E.1: Range of input parameters for *Status Quo* and *Progress adjustable tool* for steady ranking

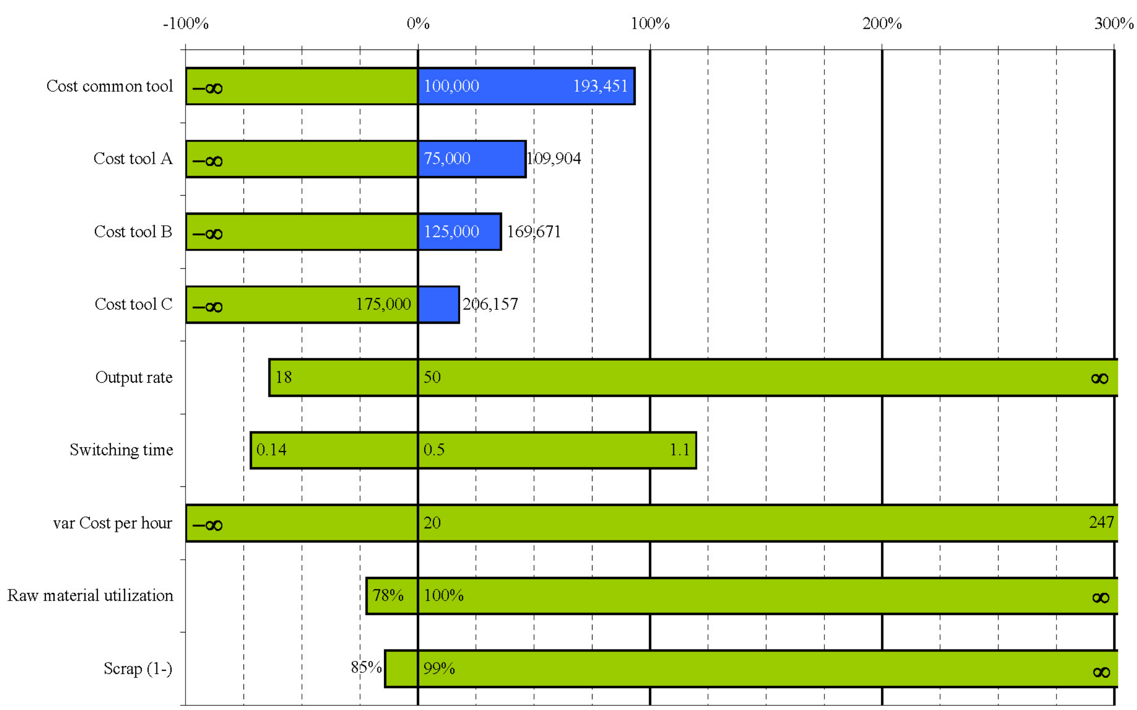

Figure E-1: Range of input parameters for *Status Quo* and *Progress adjustable tool* for steady ranking

Not surprisingly, the 'modular tooling' program is most sensitive to switching times.

*limited by tool account

Laser beam

Parameter	Min value	Actual value	Max value
Costs common tool C_{Tc}	-	10,000	10,430*
Output rate r_{Output}	2	4	15
Variable costs C_{v_H}	-	50	275
Raw material utilization r_{Mat}	43%	90%	-
Useful parts $(1 - r_{Scrap})$	67%	95%	-

Table E.2: Range of input parameters for *Status Quo* and *Laser beam* for steady ranking

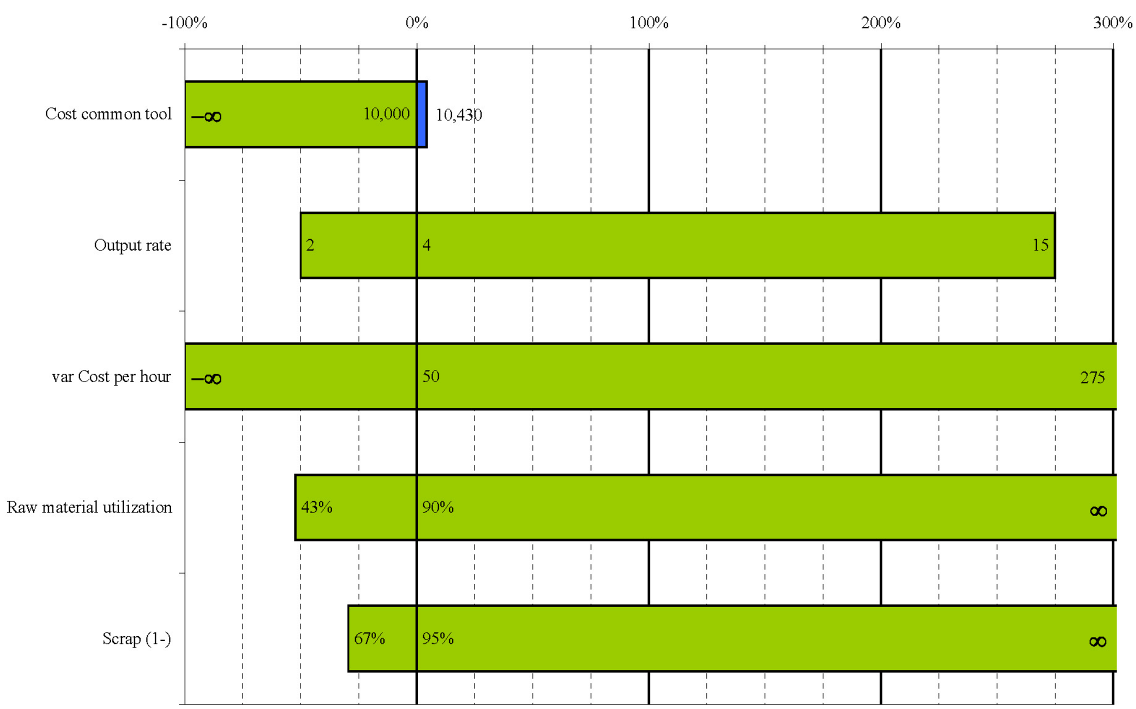

Figure E-2: Range of input parameters for *Status Quo* and *Laser beam* for steady ranking

The crucial input parameter for this process is the output rate. When it is below two parts per minute *Laser beam* continues to drop back.

Punching

Parameter	Min value	Actual value	Max value
Costs common tool C_{Tc}	19,172*	20,000	75,441*
Output rate r_{Output}	4	10	15
Variable costs C_{v_H}	-	30	497
Raw material utilization r_{Mat}	43%	85%	-
Useful parts $(1 - r_{Scrap})$	62%	98%	-

Table E.3: Range of input parameters for *Status Quo* and *Punching* for steady ranking

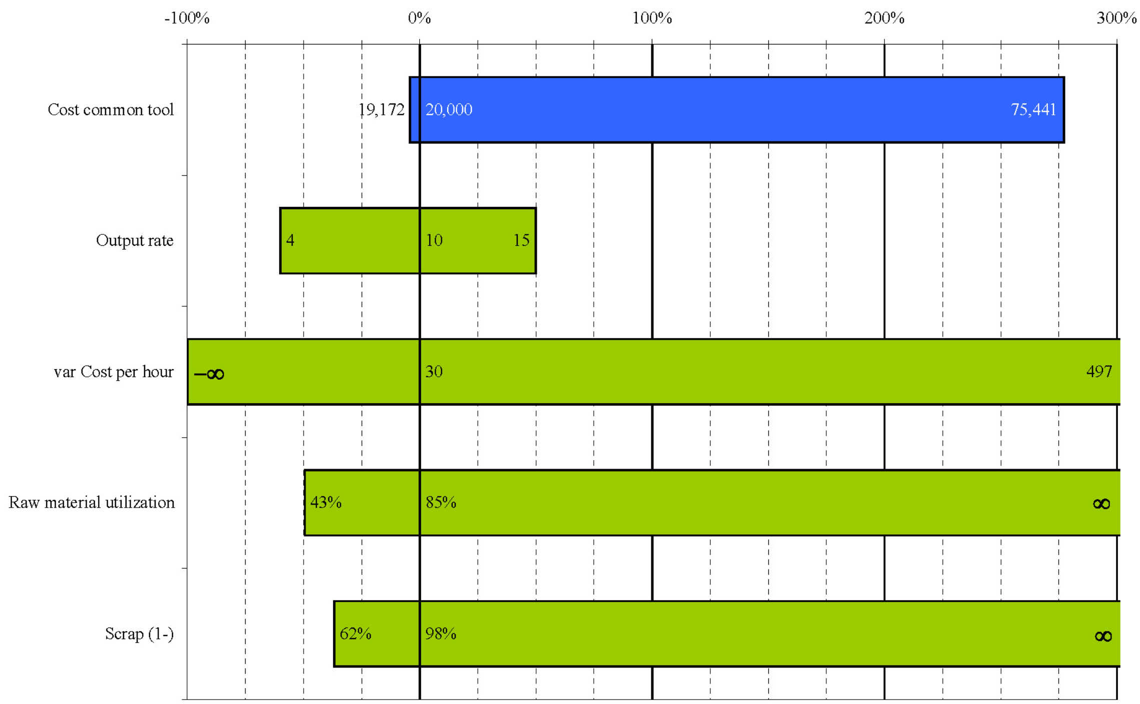

Figure E-3: Range of input parameters for *Status Quo* and *Punching* for steady ranking

Here too, the output rate is the most sensitive parameter. Important to notice is that if the cost for the common tool are cut down just a bit, *Punching* advances in the ranking of the tool account.

Milling

Parameter	Min value	Actual value	Max value
Costs common tool C_{Tc}	6,627*	25,000	49,707*
Output rate r_{Output}	-	1	3
Variable costs C_{v_H}	-	30	-
Raw material utilization r_{Mat}	-	100%	-
Useful parts $(1 - r_{Scrap})$	-	98%	-

Table E.4: Range of input parameters for *Status Quo* and *Milling* for steady ranking

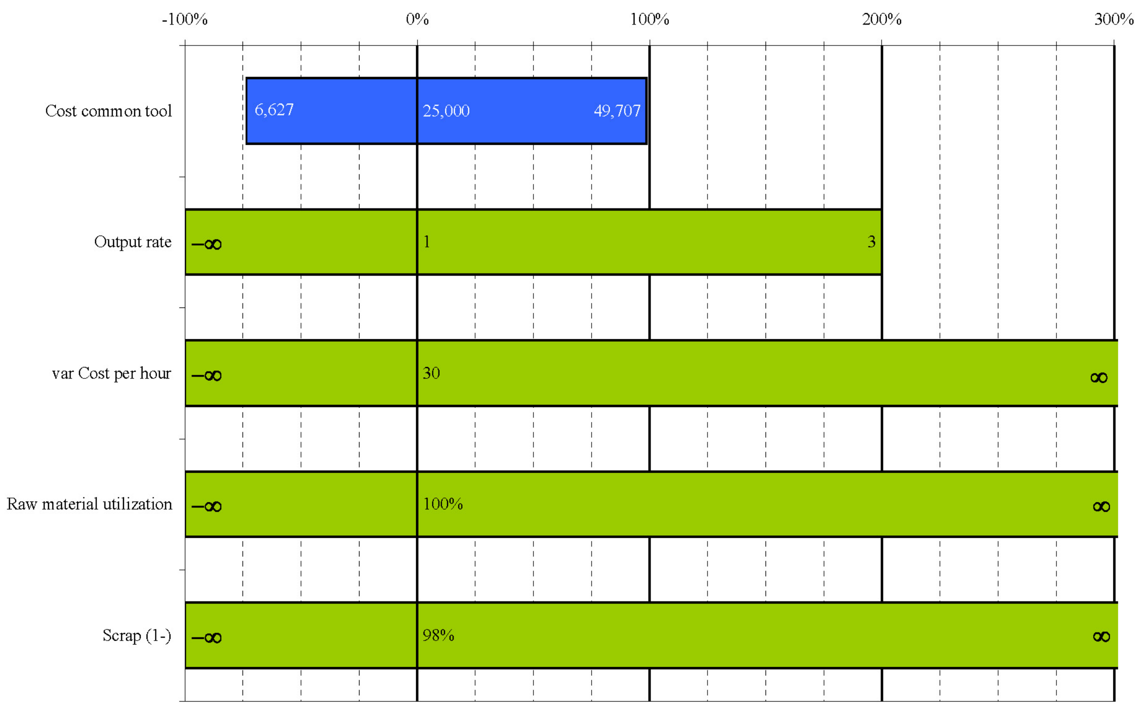

Figure E-4: Range of input parameters for *Status Quo* and *Milling* for steady ranking

Here, only two parameters are sensitive to the rankings. If the output rate is set higher than three, *Milling* gets ahead of *Laser beam*. Changes in the ranking of the tool account happen if the costs for the common tool are varied plus or minus about 90% from its actual value.

General parameters

Parameter	Min value	Actual value	Max value
Workdays n_D	32	250	-
Shifts n_S	-	1	-
Work hours n_H	2	7	-
Overhead $r_{Overhead}$	-	15%	157%
Material price C_{Mat_U}	-	0.95	2.36
Stock keeping r_{Stock}	-	25%	-
Overdue $r_{Overdue}$	-	80%	-
Machine cost C_M	783,000	5,000,000	39,105,000
Machine lifetime T_{LM}	2	10	63
Tool lifetime T_{LT}	976,000	1,000,000	3,597,000

Table E.5: Range of general input parameters for *Status Quo* for steady ranking

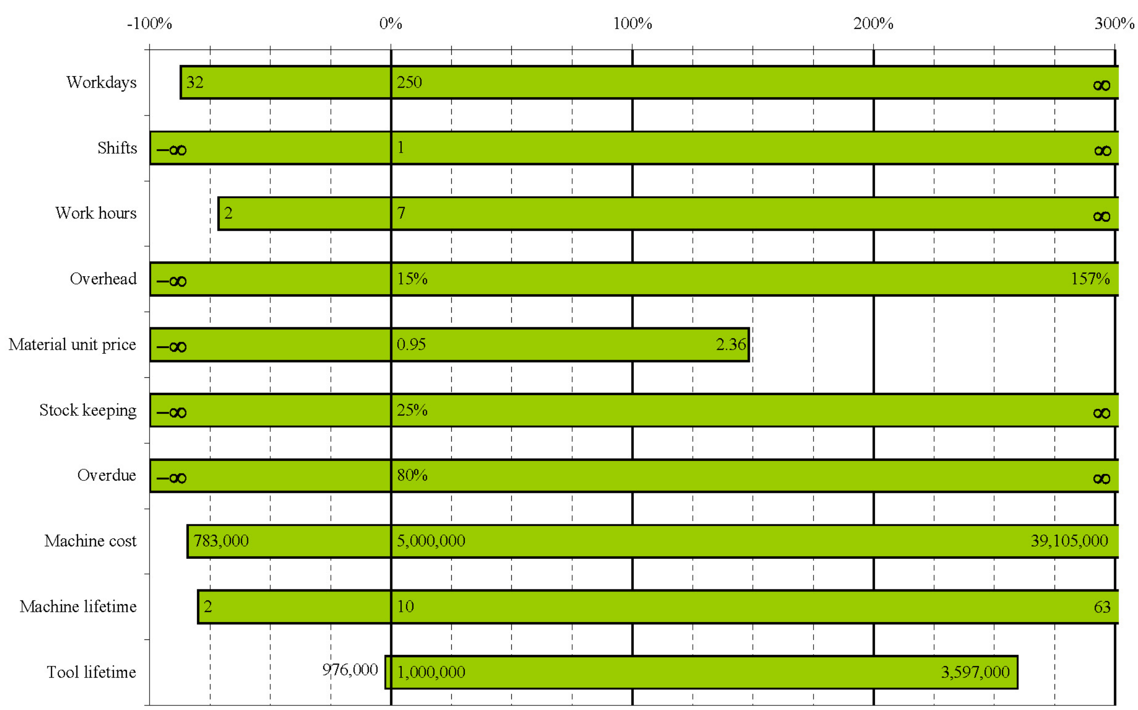

Figure E-5: Range of general input parameters for *Status Quo* for steady ranking

The general input parameters are not that sensitive, since they are the same for all processes. Nevertheless, if the tool lifetime is reduced by 2.4% a change in the ranking of the earnings takes place.

Appendix F

The Lever in Aerospace Industry: Results

The results of the 'lever problem in the aerospace industry' as posed in Section 3.4 are listed here. The findings of *Status Quo* are discussed in Section 3.4.2. Since the results of the various market scenarios are more or less all the same, the rationales for the results are the same as stated already in Sections 3.4 and 3.3.1. Hence, they will not be repeated here.

The figures are all set to the same scales so that the diagrams are easily comparable.

Process scenario	Earnings E_{Tot}			
	Mean	Min	Max	STD
Dedicated tool	113,597	103,101	128,429	4,731
Adjustable tool	61,688	51,149	74,404	4,269
Laser beam	154,698	144,039	170,552	4,993
Punching	162,817	151,579	179,483	5,239
Milling	119,318	110,977	131,638	3,934
Infeed	154,635	143,426	171,099	5,180
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	597,289	597,130	597,398	49
Adjustable tool	473,112	472,917	473,242	62
Laser beam	9,937	9,931	9,942	2
Punching	19,875	19,863	19,885	4
Milling	24,843	24,828	24,856	5
Infeed	149,059	148,971	149,135	31
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	0.152	0.141	0.167	0.005
Adjustable tool	0.152	0.141	0.167	0.005
Laser beam	1.900	1.764	2.090	0.059
Punching	0.760	0.706	0.836	0.024
Milling	7.599	7.056	8.358	0.236
Infeed	0.253	0.235	0.279	0.008

Table F.1: Results of the simulation for *Status Quo*

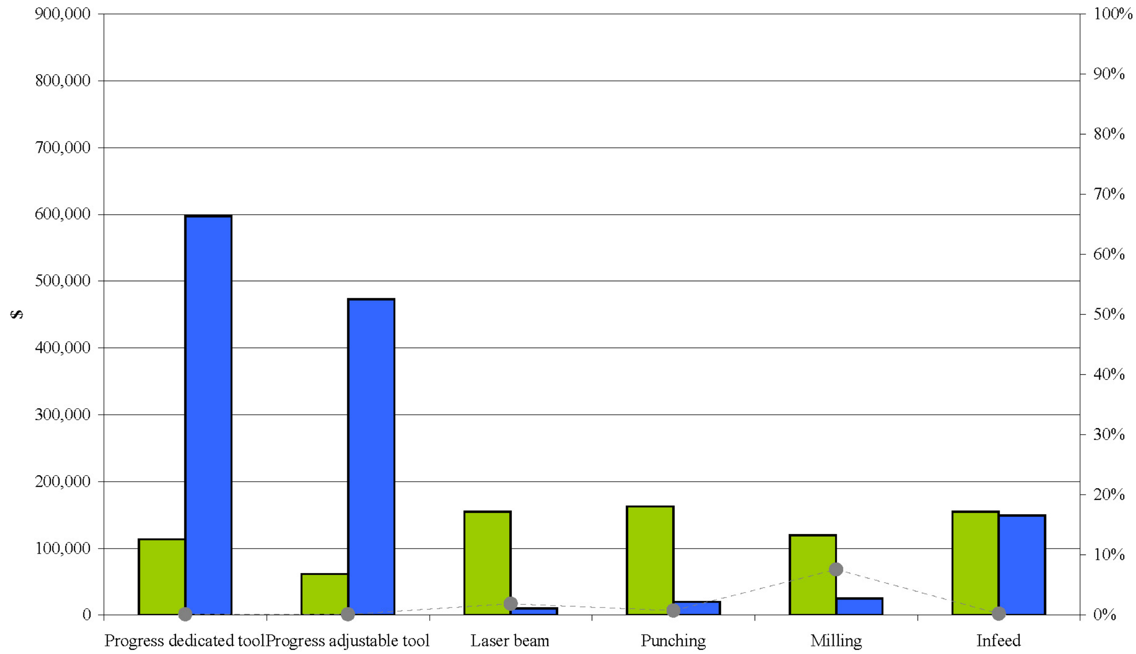

Figure F-1: Results of the simulation for *Status Quo*

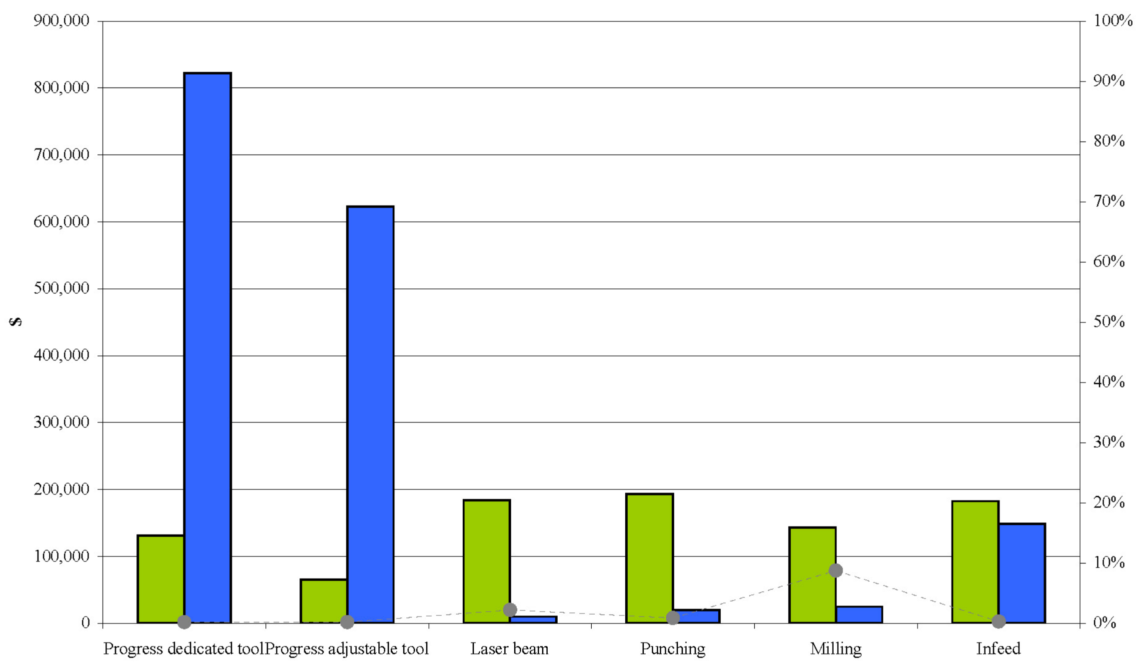

Figure F-2: Results of the simulation for *Plus D*

Process scenario	Earnings E_{Tot}			
	Mean	Min	Max	STD
Dedicated tool	130,676	115,903	146,996	5,233
Adjustable tool	65,262	51,955	79,478	4,728
Laser beam	183,673	168,363	201,120	5,618
Punching	193,019	177,002	211,216	5,876
Milling	142,985	130,748	157,188	4,511
Infeed	182,556	166,554	200,450	5,858
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	822,015	821,849	822,163	55
Adjustable tool	622,811	622,603	622,987	67
Laser beam	9,925	9,921	9,932	2
Punching	19,850	19,841	19,863	4
Milling	24,812	24,801	24,829	6
Infeed	148,871	148,809	148,976	33
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	0.175	0.162	0.189	0.005
Adjustable tool	0.175	0.162	0.189	0.005
Laser beam	2.185	2.020	2.360	0.062
Punching	0.874	0.808	0.944	0.025
Milling	8.741	8.080	9.438	0.248
Infeed	0.292	0.269	0.315	0.008

Table F.2: Results of the simulation for *Plus D*

Process scenario	Earnings E_{Tot}			
	Mean	Min	Max	STD
Dedicated tool	107,720	96,984	116,141	4,101
Adjustable tool	44,662	33,961	53,163	4,056
Laser beam	160,757	150,407	169,165	4,002
Punching	168,401	157,716	177,152	4,169
Milling	127,549	118,632	134,475	3,294
Infeed	157,864	147,095	166,622	4,186
	Account tool V_{Fin}			
	Mean	Min	Max	STD
Dedicated tool	648,377	648,299	648,466	39
Adjustable tool	522,940	522,832	523,061	51
Laser beam	9,950	9,947	9,953	1
Punching	19,900	19,894	19,907	3
Milling	24,875	24,868	24,884	3
Infeed	149,250	149,206	149,302	21
	Machine utilization $r_{Machine}$			
	Mean	Min	Max	STD
Dedicated tool	0.143	0.135	0.149	0.003
Adjustable tool	0.143	0.135	0.149	0.003
Laser beam	1.784	1.684	1.869	0.042
Punching	0.714	0.673	0.747	0.017
Milling	7.137	6.734	7.474	0.169
Infeed	0.238	0.224	0.249	0.006

Table F.3: Results of the simulation for *Greek*

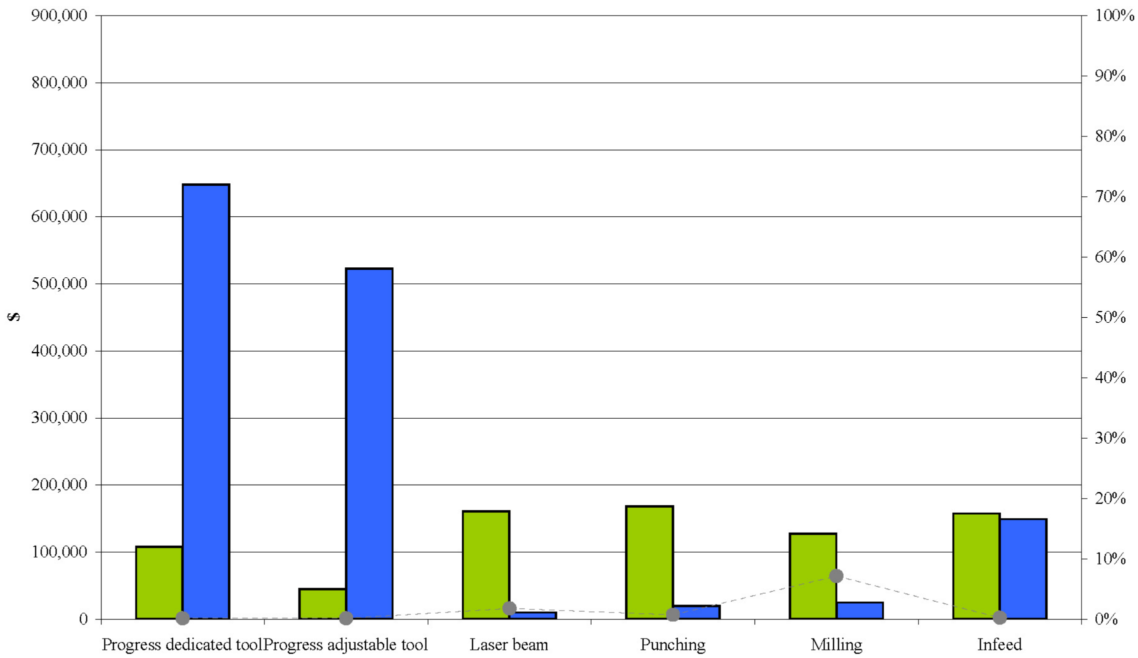

Figure F-3: Results of the simulation for *Greek*

Appendix G

Critera Comparison Analyses

For testing the parameters embedded in the criteria comparison analysis in Chapter 4, some 'test parts' are made. The *lever in the automotive industry* and the *lever in the aerospace industry* are discussed here. More test parts can be found on the CD, see Appendix H.

G.1 Choice of Process

G.1.1 Lever Auto

Figure G-1 shows the results of the criteria comparison analysis for the lever in the automotive industry. The *lever auto* is assumed to be produced in high volumes, but with a rather low demand fluctuation. Its product mix is small, only three and four parts, respectively. The part set is defined to be stable with a low speed of change and also a low speed of reaction. The part's size is small, it is two dimensional and not complex. The lever has no load requirements.

The results show, that forming is the best manufacturing process for the *lever auto*. Other possible technologies are punching or forging. Now, the table shows in a clear way that it can not include any technological knowledge, e.g., the table cannot make any feasibility decisions.

	Attribute	Weight	Characteristic	Lever Auto	Machining	Forming	Punching	Casting	Rapid Prototyping	Laser beam cutting	Water jet cutting	Forging
Market	Volume	14	High	1	1	3	0	0	0	0	0	1
			Low		2	0	3	3	3	3	3	2
	Demand fluctuation	5	High		1	2	1	1	0	1	1	2
			Low	1	2	1	2	2	3	2	2	1
	Product mix	9	Big		3	0	2	3	3	3	3	1
			Small	1	0	3	1	0	0	0	0	2
	Stability of part set	7	High	1	1	3	1	2	0	0	0	2
			Low		2	0	2	1	3	3	3	1
	Speed of Change	12	High		2	0	2	0	3	2	2	1
			Low	1	1	3	1	3	0	1	1	2
	Speed of Reaction	3	High		3	0	3	1	3	3	3	1
			Low	1	0	3	0	2	0	0	0	2
Part	Parts' size	10	Big		1	2	0	1	2	1	1	1
			Small	1	2	1	3	2	1	2	2	2
	Dimensionality	20	2D	1	0	1	3	1	2	3	2	1
			3D		3	2	0	2	1	0	1	2
	Complexity of Part	10	High		3	2	0	3	2	2	2	1
			Low	1	0	1	3	0	1	1	1	2
	Load Requirement	10	Yes		1	3	1	3	0	1	2	3
			No	1	2	0	2	0	3	2	1	0
Sum					83	180	178	106	105	132	102	141
Rank					8	1	2	5	6	4	7	3

Figure G-1: Criteria comparison analysis for lever auto manufacturing processes

G.1.2 Lever Aero

In Figure G-2 the outcome for the analysis for the lever in the aerospace industry is shown. In comparison to the *lever auto*, this part is produced in low volumes, but therefore demand fluctuates highly. The other characteristics are the same as in the first case.

Now, not forming, but punching is the best process. It is followed by laser beam cutting and forging. These results are congruent with those of Chapter 3.

G.2 Choice of Type of Flexibility

G.2.1 Lever Auto

For *lever auto*, as can be seen in Figure G-3, the most important flexibilities are operation and routing flexibility, followed by expansion and market flexibility. This

	Attribute	Weight	Characteristic	Lever Aero	Machining	Forming	Punching	Casting	Rapid Prototyping	Laser beam cutting	Water jet cutting	Forging
Market	Volume	14	High		1	3	0	0	0	0	0	1
			Low	1	2	0	3	3	3	3	3	2
	Demand fluctuation	5	High	1	1	2	1	1	0	1	1	2
			Low		2	1	2	2	3	2	2	1
	Product mix	9	Big		3	0	2	3	3	3	3	1
			Small	1	0	3	1	0	0	0	0	2
	Stability of part set	7	High	1	1	3	1	2	0	0	0	2
			Low		2	0	2	1	3	3	3	1
	Speed of Change	12	High		2	0	2	0	3	2	2	1
			Low	1	1	3	1	3	0	1	1	2
	Speed of Reaction	3	High		3	0	3	1	3	3	3	1
			Low	1	0	3	0	2	0	0	0	2
Part	Parts' size	10	Big		1	2	0	1	2	1	1	1
			Small	1	2	1	3	2	1	2	2	2
	Dimensionality	20	2D	1	0	1	3	1	2	3	2	1
			3D		3	2	0	2	1	0	1	2
	Complexity of Part	10	High		3	2	0	3	2	2	2	1
			Low	1	0	1	3	0	1	1	1	2
	Load Requirement	10	Yes		1	3	1	3	0	1	2	3
			No	1	2	0	2	0	3	2	1	0
Sum					92	143	215	143	132	169	139	160
Rank					8	4	1	4	7	2	6	3

Figure G-2: Criteria comparison analysis for lever aero manufacturing processes

result may be astonishing since one may have expected product or volume flexibility to occur on the winning list. Because the part is characterized very abstractly, this result emerged probably more due to the lack of any significant specification than to really a need for one of those flexibilities. This conclusion is supported by the fact that range of the sums for the different flexibilities is very tight.

G.2.2 Lever Aero

Figure G-4 shows the results for the analysis in the case of *lever aero*. Due to the high demand volatility, volume flexibility comes out as the most important flexibility. Comprehensible are also operation and routing flexibility as followers on the ranking list. Since the product is manufactured on multipurpose machinery, an increase in those flexibilities may be valuable.

`	Attribute	Weight	Characteristic	Lever Auto	Machine Flexibility	Material Handling Flexibility	Operation Flexibility	Process Flexibility	Routing Flexibility	Product Flexibility	Volume Flexibility	Expansion Flexibility	Program Flexibility	Production Flexibility	Market Flexibility
Market	Volume	3	High	1	1.5	1.5	1.5	1.5	1.5	1.5	1	1.5	3	1.5	1.5
			Low		1.5	1.5	1.5	1.5	1.5	1.5	2	1.5	0	1.5	1.5
	Demand fluctuation	20	High		2	1.5	2	1.5	2	1.5	3	2	2	1.5	2
			Low	1	1	1.5	1	1.5	1	1.5	0	1	1	1.5	1
	Product mix	10	Big		3	3	2	3	2	1.5	2	2	3	3	1
			Small	1	0	0	1	0	1	1.5	1	1	0	0	2
	Stability of part set	17	High	1	1	1	1.5	1	1.5	0	1	1	1	1	1
			Low		2	2	1.5	2	1.5	3	2	2	2	2	2
	Speed of Change	7	High		3	2	2	2	2	3	1.5	1.5	1.5	2	2
			Low	1	0	1	1	1	1	0	1.5	1.5	1.5	1	1
	Speed of Reaction	13	High		2	2	1.5	2	1.5	3	1.5	1.5	1.5	2	2
			Low	1	1	1	1.5	1	1.5	0	1.5	1.5	1.5	1	1
Parts	Parts' Sizes Range	12	Wide		2	2	1.5	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			Small	1	1	1	1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Dimensionality	9	2D	1	1.5	2	1.5	2	1.5	1	1.5	1.5	1.5	1	1.5
			3D		1.5	1	1.5	1	1.5	2	1.5	1.5	1.5	2	1.5
	Complexity of Part	6	High		2	2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	1.5
			Low	1	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1.5
	Load Requirement	3	Yes		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			No	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sum					91	112	132	103	132	90	105	127	121	109	127
Rank					10	6	1	9	1	11	8	3	5	7	3

Figure G-3: Criteria comparison analysis for lever auto flexibilities

`	Attribute	Weight	Characteristic	Lever Aero	Machine Flexibility	Material Handling Flexibility	Operation Flexibility	Process Flexibility	Routing Flexibility	Product Flexibility	Volume Flexibility	Expansion Flexibility	Program Flexibility	Production Flexibility	Market Flexibility
Market	Volume	3	High		1.5	1.5	1.5	1.5	1.5	1.5	1	1.5	3	1.5	1.5
			Low	1	1.5	1.5	1.5	1.5	1.5	1.5	2	1.5	0	1.5	1.5
	Demand fluctuation	20	High	1	2	1.5	2	1.5	2	1.5	3	2	2	1.5	2
			Low		1	1.5	1	1.5	1	1.5	0	1	1	1.5	1
	Product mix	10	Big		3	3	2	3	2	1.5	2	2	3	3	1
			Small	1	0	0	1	0	1	1.5	1	1	0	0	2
	Stability of part set	17	High	1	1	1	1.5	1	1.5	0	1	1	1	1	1
			Low		2	2	1.5	2	1.5	3	2	2	2	2	2
	Speed of Change	7	High		3	2	2	2	2	3	1.5	1.5	1.5	2	2
			Low	1	0	1	1	1	1	0	1.5	1.5	1.5	1	1
	Speed of Reaction	13	High		2	2	1.5	2	1.5	3	1.5	1.5	1.5	2	2
			Low	1	1	1	1.5	1	1.5	0	1.5	1.5	1.5	1	1
Parts	Parts' Sizes Range	12	Wide		2	2	1.5	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			Small	1	1	1	1.5	0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Dimensionality	9	2D	1	1.5	2	1.5	2	1.5	1	1.5	1.5	1.5	1	1.5
			3D		1.5	1	1.5	1	1.5	2	1.5	1.5	1.5	2	1.5
	Complexity of Part	6	High		2	2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2	1.5
			Low	1	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1.5
	Load Requirement	3	Yes		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
			No	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sum					111	112	152	103	152	90	168	147	132	109	147
Rank					8	7	2	10	2	11	1	4	6	9	4

Figure G-4: Criteria comparison analysis for lever aero flexibilities

Appendix H

Content of the CD

The CD enclosed at the end of this report contains the following data:

- Figures
  - All figures in this report in *.jpg format
- Literature
  - 1_Literature.doc (Provides links to all summaries and articles)
  - Summaries of articles
  - Articles in *.pdf format
- Presentations
  - Final presentation.ppt
  - Flexibilitaetsarten.doc (Übersichtstabelle der Flexibilitätsarten)
  - Lever problem.ppt (Presentation about the approach for the lever problem)
  - Types of flexibilities.doc (Overview table of Sethi and Sethi's flexibilities)
  - Types of Flexibilities.ppt ('Animated' presentation of flexibility types)
- Report

  - Thesis_A4-1.pdf (This report in A4 paper size for one-sided printing or reading on screen)
  - Thesis_A4-2.pdf (This report in A4 paper size for double-sided printing)
  - Thesis_letter-1.pdf (This report in letter paper size for one-sided printing or reading on screen)
  - Thesis_letter-2.pdf (This report in letter paper size for double sided printing)

- Spreadsheets
  - Brownian Motion.xls (Simulation of demand with geometric brownian motion)
  - CC analysis.xls (Comparison of different parts in regards on processes and flexibility)
  - Cost analysis Aero.xls (Analysis of input parameters in the lever problem in the aerospace case)
  - Cost analysis Auto.xls (ditto for the automotive case)
  - Cost sim Aero.xls (Simulation tool for the lever problem in the aerospace case)
  - Cost sim Auto.xls (ditto for the automotive case)
  - Results Aero.xls (Simulation results for the lever in the aerospace case)
  - Results Auto.xls (ditto for the automotive case)

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