Thema: Development of a tool for consistent assessment of resource efficiency in small and medium-sized enterprises
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Abstract

Resource efficiency has become an important topic due to dramatic increase of world-population and globalization. A company that is not able to efficiently utilize its resources is less sustainable. It produces at higher cost as well as with higher environmental impact. Especially small and medium-sized enterprises are mostly not able to deal with these kinds of issues in addition to their daily business. Their characteristics differentiate them from large companies and require approaches that respond to their specific needs. Not only technological aspects but also organizational problems as well as lack of methodology are reasons for low resource efficiency in small companies. This thesis therefore focuses on developing a tool which facilitates the increase of resource efficiency particularly for small and medium-sized enterprises.

To start with, this thesis investigates the meaning of resource efficiency and the basics of performance measures as well as special characteristics of small and medium-sized enterprises. Afterwards, measures are designed in order to quantify resource efficiency. A case study is carried out as well to investigate how to ensure applicability of a supporting tool in small and medium-sized enterprises from different industries. In the final part, a computer-based tool is developed which facilitates the assessment of resource efficiency potentials using 12 resource efficiency measures, a consistent approach and a ranking method.

Keywords: Resource efficiency, performance measures, small and medium-sized enterprises
# Table of contents

Abstract .......................................................................................................................... IV  
Table of contents .......................................................................................................... V  
List of figures ................................................................................................................ VIII  
List of tables ................................................................................................................ X  
Acknowledgement ......................................................................................................... XI  

1 **Introduction** ......................................................................................................... 1  
   1.1 Problem description and project context ............................................................. 1  
   1.2 Objective and delimitations .............................................................................. 3  
   1.3 Outline of the thesis ......................................................................................... 4  

2 **Literature review** .................................................................................................. 5  
   2.1 Resource efficiency ............................................................................................ 5  
      2.1.1 The term resource efficiency ..................................................................... 5  
      2.1.2 Terms related to resource efficiency ......................................................... 8  
      2.1.3 Unit process model ................................................................................... 11  
   2.2 Performance measurement and small and medium-sized enterprises .......... 13  
      2.2.1 Performance measures ............................................................................ 13  
      2.2.2 Performance objectives ........................................................................... 16  
      2.2.3 Characteristics of small and medium-sized enterprises ......................... 18  
   2.3 The problem of analyzing resource efficiency ............................................... 20  
   2.4 Summary .......................................................................................................... 22  

3 **Research approach** ............................................................................................ 23  

4 **Development of resource efficiency measures** ................................................... 26  
   4.1 Designing measures ......................................................................................... 26  
      4.1.1 Energy ....................................................................................................... 27  
      4.1.2 Environment .............................................................................................. 29  
      4.1.3 Human resources ....................................................................................... 29
4.1.4 Logistics ............................................................................................................30
4.1.5 Machining and manual activities.................................................................32
4.1.6 Material ...........................................................................................................34
4.1.7 Quality ............................................................................................................35
4.2 Overview ..........................................................................................................36

5 Case study research in small and medium-sized enterprises ........................39
5.1 Formulation of a study question .....................................................................39
5.2 Formulation of study propositions ..................................................................39
5.3 Definition of the unit of analysis ....................................................................41
5.4 Relation of obtained data and propositions ..................................................41
5.4.1 Relevant aspects ..........................................................................................42
5.4.2 Appropriate aspects ....................................................................................44
5.5 Criteria for interpreting the study’s findings ..................................................46

6 Development of a computer-based tool for consistent assessment of resource efficiency .....................................................................................................................49
6.1 Development of a ranking method .................................................................50
6.1.1 Classification of resource efficiency measures ........................................50
6.1.2 Design of an evaluation method for value-adding resources ..................52
6.2 Development of a software program .............................................................57
6.2.1 General conditions .....................................................................................58
6.2.2 Requirements and software platform .......................................................60
6.2.3 User interface design ..................................................................................61
6.3 Development of a consistent assessment approach ......................................63
6.3.1 6 steps for assessing resource efficiency ..................................................64
6.3.2 Exemplary application ................................................................................66

7 Discussion of results .........................................................................................73

8 Conclusion and future work ............................................................................76

References ..............................................................................................................77
Appendix
List of figures

Figure 1: Cost structure in German industry (2008) .......................................................... 1
Figure 2: Participants of the project “Methods for Efficiency - M4E” .................................. 3
Figure 3: Outline of the thesis .............................................................................................. 4
Figure 4: Transformed and transforming resources in manufacturing using the example of drilling .......................................................... 6
Figure 5: The three dimensions of sustainability .................................................................. 7
Figure 6: Resource efficiency within efficiency and effectiveness ........................................ 9
Figure 7: Comparison of ways to improve resource efficiency and productivity ............... 10
Figure 8: Simplified unit process model ............................................................................... 12
Figure 9: Evolution of performance measures ..................................................................... 13
Figure 10: Onion model and its three types of performance measures ................................. 15
Figure 11: Performance objectives ...................................................................................... 16
Figure 12: Internal influences of performance objectives ...................................................... 20
Figure 13: Direct cost and hidden cost of resource efficiency potentials ............................ 21
Figure 14: Research approach .............................................................................................. 25
Figure 15: General model of energy consumption of a single operator in a manufacturing plant ........................................................................................................... 27
Figure 16: Concept of delivery speed for a single order ....................................................... 30
Figure 17: Dependability of delivered orders ....................................................................... 31
Figure 18: The concept of the overall equipment effectiveness .............................................. 33
Figure 19: Concept of worker efficiency ............................................................................. 34
Figure 20: Concept of material consumption ...................................................................... 35
Figure 21: Study propositions for ensuring applicability in SMEs ....................................... 41
Figure 22: Extract of interview results (multiple choice questions) ...................................... 42
Figure 23: Relevance of measures in SMEs ......................................................................... 43
Figure 24: Extract of case study: Used measures in manufacturing SMEs .......................... 44
Figure 25: Extract of case study: Availability of data for calculating measures .................. 45
Figure 26: Development of a tool for consistent assessment of resource efficiency ............ 49
Figure 27: Classification of resource efficiency measures .................................................... 51
Figure 28: Procedure of the value benefit analysis ............................................................... 53
Figure 29: Main groups of manufacturing processes according to DIN 8580 ....................... 54
Figure 30: Hierarchy of objectives based on manufacturing processes ............................... 55
Figure 31: Weighting of manufacturing processes for each resource ................................. 56
Figure 32: Example of ranking value-adding measures using 2 mass-change processes operated by a machine ......................................................... 57
Figure 33: Information flow between user and software ....................................................... 62
Figure 34: Consistent assessment approach ....................................................................... 64
Figure 35: Set the system boundary ..................................................................................... 64
Figure 36: Insert basic information into input screen ........................................................... 65
Figure 37: Basic concept of identifying data for calculating material efficiency ................ 66
Figure 38: System boundary of the exemplary application ................................................ 67
Figure 39: Daily load curves of a building (22 days) ............................................................ 68
List of tables

Table 1: Overview of resource efficiency measures .......................................................... 37
Table 2: Definitions of 6 main manufacturing process groups ......................................... 54
Table 3: Input of basic information in input screen ............................................................ 67
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1 Introduction

1.1 Problem description and project context

Already in 1972 the Club of Rome stated that limited resource supplies cannot meet the requirements of steady growth [1]. Further dramatic increase of world-population and globalization indicate a rising consumption of natural resources due to strong growing volumes of industrial manufactured products [2]. Hence, the problem of scarcity tends to grow to more acute. Governments try to lessen environmental impacts and ensure sustainability by entailing legal requirements on companies which have to be considered during processes planning and operating plants [3]. Often those are connected to financial incentives [4].

For companies resource efficiency is becoming an increasingly important topic. In industry, material cost constitutes the largest share of the overall cost [5]. Likewise prices for energy show an increasing trend [3]. Figure 1 points out the share of material and energy cost in the overall cost during 2008 in German industry. Taking this as a reference, there is evidently a high economic potential especially regarding material savings. The share of material and energy cost is more than 2.5 times larger than the usually quite popular cost of labor.

![Figure 1: Cost structure in German industry (2008)](5)
Also from the customer’s perspective environmental aspects have become important factors when making purchase decisions and can become an order winner and long-term qualifier [6]. Operating manufacturing processes in a resource efficient manner can therefore be a competitive advantage.

Nevertheless, changes regarding resource efficiency are not easy to implement and demand a lot of effort from operating companies [7]. Especially small and medium-sized enterprises (SMEs) which are known for having a rather reactive fire-fighting mentality [8] are rarely able to deal with these kinds of issues in addition to their day-to-day business. Their limited resources require approaches and models that respond to their specific needs and which are efficient and easy to implement [9]. Especially technological aspects and organizational problems as well as lack of methodology are causes for low resource efficiency [10]. Having in mind that SMEs make up 99% of all companies in Europe [11] and assuming that their cost structure is similar to the one shown in Figure 1, large potentials are existing which are quite difficult to access. This thesis therefore intends to support SMEs with a computer-based tool in order to improve resource efficiency in daily business.

Within the project “Methods for Efficiency: Development of Methods for the Sustainable Increase of Manufacturing Resource Efficiency in Small and Medium Sized Enterprises” the University of Bayreuth, the Fraunhofer IPA and the KTH Royal Institute of Technology work in cooperation with nine industrial enterprises. Six of those nine industrial enterprises are SMEs from various industries. The goal of this two-year project is to develop a comprehensive concept with methodological innovations to detect and tackle resource losses. Figure 2 gives an overview of participating research and technology organizations and industrial enterprises.
Within this scope the Department of Production Engineering at KTH develops a supporting tool for the consistent assessment of resource efficiency. Four of the six SMEs, which participate in this project, will directly contribute to this thesis.

1.2 Objective and delimitations

Given the problem description and the background of the project the objective, of the thesis can be stated as:

*Development of a tool which facilitates the increase of resource efficiency for small and medium-sized enterprises*

The result shall be a tool based on a computer platform designed particularly for SMEs.

Usually the term resource is used within the context of life cycle analysis in research. That analysis considers all stages a product passes through, from natural resources acquisition, use and recycling to final disposal [12]. This particular product based perspective is not covered in this thesis. The focus is put on SMEs and their efficiency regarding their opera-
tions on the shop floor and their resources used to run those operations. The actual product design is treated as given. Likewise, it is not the intention to establish a performance measurement system for SMEs.

1.3 Outline of the thesis

This thesis consists of a logical sequence of chapters. Initiatory, the motivation of writing this thesis is stated as well as an objective derived and formulated. The following chapter details the problem based on state of the art literature. Accordingly, a research approach is designed for further investigations. These investigations again serve as basis for finally developing a computer-based tool in order to meet the objective. In the last part, results are presented and discussed. A conclusion is drawn in the end of this thesis if the objective has been met or not. Figure 3 provides an overview about the structure of the upcoming chapters.

![Figure 3: Outline of the thesis](image)

**Chapter 1**
**Introduction**
Problem statement

**Chapter 2**
**Literature review**
Specification of the problem statement based on relevant literature

**Chapter 3**
**Research method**
Research approach based on literature review

**Chapter 4, 5 and 6**
**Solution**
Elaboration of a solution

**Chapter 7 and 8**
**Discussion and conclusions**
Summary of results which will serve as basis for discussion and conclusions
2 Literature review

The problem of limited resources has always been omnipresent. Scarcity of resources has economical as well as ecological consequences. The lower the level of resources supplies becomes, the more important the stewardship of available resources gets. Also in terms of sustainability the relevance of resource efficiency has grown, especially for companies in the manufacturing business. Large companies are aware of these issues and have lately put more effort into measuring their resource consumption by, for instance, implementing energy management systems which enable monitoring energy consumption in detailed ways [13]. On the other hand, SMEs often lack financial resources and are less organized when it comes to dealing with these kinds of issues. This chapter therefore intends to provide a basis for measuring resource efficiency in SMEs. Firstly, the meaning of resource efficiency is discussed in the context of manufacturing. Then basic ideas of performance measures and characteristics of SMEs will be introduced and put in context of resource efficiency. This chapter then closes with a summary.

2.1 Resource efficiency

The term resource efficiency has recently become quite popular. There are various contexts in which this term is used in. The following subsection examines different views more closely. In order to obtain a common understanding of what resource efficiency actually means, the expressions ‘resource’ and ‘efficiency’ are first studied separately. Then the meaning of waste and productivity is discussed within this scope. In the end, a model is introduced that is supportive in managing resource use in manufacturing.

2.1.1 The term resource efficiency

Resource

‘Resource’ is a quite general term when it comes to operation processes in manufacturing. One definition of resources is given by Bernolak in 1997 [14]:

“…all human and physical resources, i.e. the people who produce the goods or provide the services, and the assets with which the people can produce the goods or provide the servi-
ces. The resources that people use include the land and buildings, fixed and moving machines and equipment, tools, raw materials, inventories and other current assets.”

It is possible to narrow down this broad definition further by distinguishing between two types of resources: Transformed resources and transforming resources [15]. The former type of input deals with physical resources that are processed in operations, like materials, energy and information. The latter type acts upon the transformed resources and has the form of facilities and staff. Figure 4 illustrates the difference of both types of resources using the example of a drilling process which is carried out by a drilling machine and operated by a staff member.

![Figure 4: Transformed and transforming resources in manufacturing using the example drilling](image)

Efficiency

The term efficiency is not as easy to grasp as the term resource. In common language efficiency can be expressed as ‘doing things right’ [16]. There is strong consensus among researchers that efficiency is linked to utilization of resources in manufacturing [17].

Just taking these two single terms and composing them to one, ‘resource efficiency’ can simply be expressed as how well human (i.e. transforming) and physical (i.e. transformed) resources are utilized in order to achieve a desired outcome.
A more straight forward definition of resource efficiency found in literature is ‘eco-efficiency’ [18] [19] or also referred to as the environmental-economic perspective. Eco-efficiency is regarded as a part of the concept of sustainability. The concept of sustainability is based on three single perspectives: Economy, ecology and society [20]. Taking into account these three perspectives, a sustainable state shall be maintained that ‘meets the needs of the present without compromising the abilities of future generations to meet their own needs’ [21]. Within this concept, eco-efficiency considers the dimensions economy and ecology, but leaves the social dimension out of scope as shown in Figure 5. This way a given economic result shall be achieved while environmental side-effects should be lessened to a minimum or the other way around, the best economical result shall be reached given the level of maximum possible environmental impact.

![Figure 5: The three dimensions of sustainability][20]

The World Business Council for Sustainable Development simply defines eco-efficiency as ‘doing more with less’ meaning to create more goods and services while the use of resources, waste and pollution are kept at a minimum level [19].

Altogether, there are 3 objectives defined for increasing resource efficiency on the operational level [22] [19]:

- Reducing consumption of resources (input)
- Reducing emissions (output)
- Increasing benefit of used resources
Those objectives can be regarded as general approach for improving resource efficiency. It is still necessary to align these improvement approaches to superior long-term objectives, which is discussed in the following sections. At this point it is anticipated that resource efficiency should not be regarded as a goal itself, but rather as a means to an end [7].

2.1.2 Terms related to resource efficiency

In the following subsection the terms ‘waste’ and ‘productivity’ are delimitated from the term ‘resource efficiency’.

Waste

Although the term waste is used often in common language it seems difficult to specify what waste actually means if an objective definition is needed [23]. Physically, waste is “substances or objects which the holder intends or is required to dispose of” [12] [24] or “something that is discarded by someone, implicating uselessness” [23].

But who decides what is ‘useless’ or what needs to be ‘disposed of’?

Both definitions are referring to the fact that there is no use for particular objects. However, this means the term ‘uselessness’ can just be applied within a subjective notion. In simple words: ‘What counts as trash depends on who’s counting’ [25]. Depending on the individual perspective, waste might therefore as well be regarded as a resource.

One of the most common definitions regarding waste of resources in manufacturing is provided by the nature of lean thinking, i.e. ‘activities that do not add value for the customer’ [26]. The subjective notion of what is waste is left to the customer at the end of a value stream. In this way, sources of waste are identified and eliminated (seven forms of waste) [26]. But solely looking at value-adding activities does not enable to make a statement about how well resources have been utilized in manufacturing processes since the focus is exclusively put on customers. A definition of waste is needed that rather connects manufacturing processes to its environmental impacts.

Based on the ordinary value stream mapping, the US Environmental Protection Agency has developed a toolkit that aims for coordinating lean implementation and environmental management to improve business as well as environmental performance [27]. In this con-
text, the definition of environmental waste is described as ‘any unnecessary use of resources or a substance released into the air, water, or land that could harm human health or the environment’. Having in mind that resource efficiency is related to both, economical and ecological aspects as previously discussed, this definition of waste is rather matching. With regard to resource efficiency in manufacturing, waste can finally be defined as

- what does not add value to customers
- unnecessary use of resources and releases to environment
- a resource when recovered, recycled or reused

**Productivity**

When reading a definition of productivity one might assume a nearly equal meaning to the term resource efficiency. Productivity is "how much and how well we produce from the resources used. If we produce more or better goods from the same resources, we increase productivity." [14]

Although the term productivity is closely related to the use of resources [17] there are differences in scope and focus when comparing it to resource efficiency. Generally, productivity is described as the opposite of waste as well as a relative concept of input oriented performance and output oriented performance [28]. In detail that means input oriented performance can be related to the ‘efficiency of an action’ while output oriented performance can be related to the ‘effectiveness of an action’. Based on Tangen, Figure 6 shows the relative concept of productivity using the description of an upstream and a downstream system of a transformation process.

![Figure 6: Resource efficiency within efficiency and effectiveness](image-url)
While efficiency has already been defined as ‘doing things right’, effectiveness can be specified as ‘doing the right things’ [16] focusing on how well a desired outcome is achieved. Effectiveness is therefore located at the downstream side of a transformation process. As also shown in Figure 6, resource efficiency is located on the upstream side, dealing with the efficient use of input, and only partially overlapping with the scope of productivity. Hence, using resources efficiently influences productivity, but solely using resources in an efficient way is not necessarily regarded as a successful way to increase productivity [29].

Getting back to Bernolak’s definition, resource efficiency only covers ‘how well we produce from the resources used’ but not ‘how much’. To put it in more general words, resource efficiency is aiming at increasing the utilization of resources while productivity is aiming at the creation of value [28]. Keeping productivity a purely economical related concept, resource efficiency considers ecological aspects which include environmental impacts. Depending on the particular situation both concepts might conflict or be compatible. Comparing improvement objectives of both concepts makes this problem more obvious. Figure 7 contrasts ways of improving resource efficiency with ways of improving productivity.

![Figure 7: Comparison of ways to improve resource efficiency and productivity](image)

Since productivity compares changes of output quantity to changes of input quantity, it is compatible with resource efficient principles as long as input and/or output quantities are
declining. In the other case, increased input and output of an operation often goes along with a higher amount of resource use and emissions. Consequently, conflicts might result since one objective can only be achieved at the expense of the other.

In theory there are various statements about compatibility of environmental and economical interests [6]. One theory claims there is a trade-off between both principles, i.e. one can only be achieved on cost of the other. Another argues that cost based on environmental improvement will benefit management in other fields, such as productivity and moral. A third theory states that cost regarding environmental management are repaid due to effects that lower expenditures in related areas or increases profit. Hence, it is difficult to finally appoint one theory that clearly states the relationship of environmental and economical interests.

Practice has shown though that lower environmental impacts can be achieved without giving up competitive advantages [31]. At this point the management of an organization has to decide how important environmental issues have to be weighed in relation to economical issues and what the effects this decision might have on the overall performance of an organization.

2.1.3 Unit process model

In order to illustrate relationships of inputs and outputs on the operational level, the unit process model is a useful framework. The unit process model is defined by the International Standard Organization as smallest element considered for which input and output data are quantified [12]. Usually the unit process model is used during life cycle inventory analyses as a part of life cycle assessment (LCA). Although LCA is not part of this thesis, this model divides resources into transformed and transforming resources and therefore facilitates handling questions regarding the utilization of resources.

The first step consists of setting the system boundary. This way the level of detail and the processes that are going to be analyzed are specified. All type of inflows and outflows, e.g. material or energy flows, crossing that boundary have then to be captured and measured, so that different kinds of resources can be balanced [3].
Figure 8: Simplified unit process model [32]

Flows in horizontal direction represent directly used up resources in manufacturing processes, i.e. transformed resources. After those resources have been processed inside the boundary and leave the system, they can be split up into product, reusable resources and waste. The procedure is equally done for flows going in vertical direction. Those represent indirectly used up resources for supporting manufacturing operations, i.e. transforming resources for keeping the process running. Using this approach enables an evaluation regarding efficiency of the process by balancing inflows and outflows.

One basic issue that needs to be considered when applying this model is the trade-off regarding cost and benefit of collected information. When defining system boundaries for the unit process, the level of detail and also the degree of needed information and therefore its cost of collecting it are determined at the same time. A carefully chosen system boundary can therefore be more beneficial and less costly.
2.2 Performance measurement and small and medium-sized enterprises

Since attention is put on what is measured, performance measurement can support an organization to focus on the right issues [28]. Measures are therefore an important aid for decision-making and evaluating the current situation of an organization. Since the main objective of this thesis is the improvement of resource efficiency, performance measurement plays an important role when it comes to quantifying efficiency. Therefore, performance measurement and characteristics of SMEs is introduced briefly in the following sections.

2.2.1 Performance measures

The field of performance measurement has steadily advanced from traditional financial measurement to a rather multi-dimensional orientation of measures in the last few decades [31] as depicted in Figure 9.

![Figure 9: Evolution of performance measures [31]](image)

After 1960 attention moved away from purely cost-based measures towards total productivity measures since they provided a more detailed view about the overall performance of an organization. Afterwards, quality issues were of major significance until a rather multi-
dimensional view evolved, which initially has been introduced by the balanced scorecard in 1992 [33]. Hence, today’s understanding of a well-functioning performance measurement system is a rather balanced set of measures. Separating internal from external views as well as financial from non-financial views results in a broader overall perspective. In doing so, the risk of adopting a narrow focus can be avoided [34].

By now, performance measurement is understood as “the process of quantifying the efficiency and effectiveness of action”, while a single performance measure can be defined as “metric used to quantify the efficiency and/or effectiveness of an action” [35]. In this thesis most attention is given to the efficiency of an action when discussing resource efficiency in the following chapters.

When it comes to designing measures one first has to be clear about what to measure before answering the question how to measure [36]. The task of designing the actual equation might then become quite challenging since there are various recommendations that should be considered in order to ensure appropriateness of a measure [28] [33] [34] [37]:

- objective criteria should be used in the equation before subjective
- use ratios instead of absolute numbers
- use group measures rather than measures based on individual performance
- the equation should stimulate improvement
- the equation should be designed in consultation with people whose performance is measured
- the equation should be easily measured and easily understood
- the equation should be as accurate as possible
- the equation should have an appropriate precision

Sometimes not all of the mentioned recommendations can be met, so that it is not possible to find ‘the right’ measure.

Performance measures also have behavioral impacts if they are implemented [34]. The impact a measure has on an individual’s behavior needs to be considered during design, especially when rewards are tied to the measure. This must be done in order to induce the correct actions. Proper alignment of the induced action to the overall goals of an organization must be ensured in order to succeed. For instance, measures based on time induce a certain working pace, which e.g. might cause the worker not to focus as much on quality, but rather on getting the job done as fast as possible. As mentioned before, in this case a
bundle of different measures needed to adequately display an operation’s overall performance.

Another general problem when establishing performance measurement systems is finding a balance between a small amount of key measures and a large amount of detailed measures [15]. Normally a compromise is found if measures are defined that reflect strategic objectives and link overall strategy of an organization to a large amount of detailed measures. Those few measures then focus on the most critical aspects for current and future success of the company. In other words, they are ‘key’ to a company’s business. In literature measures that reflect strategic objectives are called key performance indicators [38]. Parmenter uses an onion analogy to describe the connections of 3 types of performance measures as shown in Figure 10.

![Figure 10: Onion model and its three types of performance measures [38]](image)

The outside skin describes the general condition of the onion resulting from many actions over several past time periods. As more and more layers are peeled off, the more information is found until the core is reached. While the outside skin represents key result indicators which summarize the overall result from a retrospective, the different layers beneath the onion’s skin stand for performance indicators. Performance indicators are mostly a large amount of detailed measures which complement few key performance indicators, i.e. the core of the onion. In order to derive key performance indicators, strategy needs to be defined and formulated clearly by the management. This consequently leads to a determination of crucial measures for the organization’s long-term success. Once it has been de-
cided which measures are ‘key’ to an organization’s success, key performance indicators are used to increase performance dramatically.

Coming back to the topic of resource efficiency, a company needs to position the relevance of resource utilization within their corporate strategy. This will then enable easier decision-making regarding environmental and economical issues and also facilitates focusing on the right measures.

2.2.2 Performance objectives

Among other things, the previous subsection has shown that measures need to be aligned to an organization’s critical success factors. In this way the focus can be put on measures which influence the overall performance of an organization. The overall performance of an organization can also be broken down into 5 general performance objectives. Each of these performance objectives contributes to satisfy stakeholder needs. According to Slack et al. these objectives consist of quality, dependability, speed, flexibility and cost [15] as depicted in Figure 11.

![Figure 11: Performance objectives [15]](image)

All 5 performance objectives are introduced in a few words.
**Speed** describes the time period between a customer’s request of a product and receiving it. Quick decision-making as well as fast movement of material and information inside an organization enables fast response to customer demands.

**Quality** can be described as the conformance to customer expectations. It is mostly the most tangible part of an operation. The effectiveness of an operation can be evaluated by satisfaction or dissatisfaction of the customer.

**Flexibility** is the ability to change operations. Being flexible can be understood in four different ways.

- **Product flexibility:** Ability to introduce new or modified products
- **Mix flexibility:** Ability to produce wide ranges or mixes of products
- **Volume flexibility:** Ability to change levels of produced quantities over time
- **Delivery flexibility:** Ability to change timings of deliveries

One quite tremendous example of high flexibility is called mass customization which means producing products at a high volume while being able to keep the products customized at the same time.

**Dependability** means being in time regarding customers receiving their products when they are needed.

**Cost** is universally an attractive objective since products can be offered at lower prices. Mostly productivity measures are used to express how well an operation is doing in terms of cost.

There are different theories about how those 5 performance objectives are related to each other. The sandcone model states that all 5 objectives can be met, if a unique sequence is followed when tackling the performance objectives [39]. On the other hand, the trade-off theory states that trying to improve one objective comes at expense of another performance objective. As a result, an organization would be better off if focus is put just on one or a few objectives instead of all [15].

As also shown in Figure 11 all performance objectives have external and internal effects. External effects are related to stakeholders outside the organization while internal effects deal with operations inside the organization. Every performance objective affects cost in-
ternally. Since this thesis deals with resource efficiency, the internal effects resulting from resource utilization are of major concern.

Efficient or inefficient use of resources is directly reflected by the cost of the organization. Hence, cost can be regarded as an indicator that sums up the overall internal performance of an organization, including how well resources have been used. Nevertheless, cost is a financial measure which can only be retrieved from a retrospective. Its informative value is limited since it cannot reveal how well an organization has done in terms of efficiency [40]. That is why additional measures are needed to quantify resource efficiency of an organization from various perspectives.

Apart from those performance objectives and cost-related motivation, there are additional factors that need to be considered when dealing with resource efficiency. Taking into account the ecological view which focuses on scarcity, environmental impacts or changes in climate can also result in competitive advantages [7]. As stated in the previous subsection, it is finally up to the management to decide what long-term objectives should be tracked and what role resource efficiency is playing within corporate strategy. Yet, competitive advantages resulting from improved resource utilization have to be put in context of a company’s long-term goals.

2.2.3 Characteristics of small and medium-sized enterprises

There are several definitions regarding to what size an enterprise is regarded as a small or medium-sized enterprise. Within this thesis SMEs are defined as enterprises whose number of employees is below 500 and sales revenue less than 50 million euro [41]. In many economies SMEs are large in number and they generally differ very much from large companies [42]. There is a set of certain characteristics which are introduced briefly [9] [43]:

*Lack of human and capital resources: *SMEs almost exclusively focus on daily business. There is rarely any time for additional activities or financial expenses besides the daily job.

*Managerial capacity:* As indicated by the preceding argument, administrative activities are rather neglected since major attention is given to products and operational processes. Barely any capacity is reserved for keeping the overall perspective.
Reactive approach: SMEs are known for a rather short-term orientation and reactive behavior. This is said to result from a lack of strategy and methodologies.

Tacit knowledge and little attention given to the formalization of processes: SMEs are known for their high degree of specialization and knowledge. On the other hand, their management processes are mostly structured poorly, which hinders organizational development.

High degree of flexibility: SMEs have a high ability to react quickly to competitive actions and external changes in their business environment. Due to their convenient size and low organizational structures, decision-making processes are typically more efficient and effective in comparison to large firms.

Another major distinction between SMEs and large firms is the greater external uncertainty in which SMEs operate [9]. Therefore the ability of SMEs to adapt to changes is of major importance. Hence, flexibility is considered as the most valuable and suitable advantage SMEs have compared to large firms [43]. Having in mind the five performance objectives, which have been discussed in the previous section, the performance objective ‘flexibility’ clearly overweighs the other objectives when dealing with SMEs. One might even argue that an SME’s reactive behavior results from particularly this superior ability. That is, SMEs are reactive because they are able to adjust immediately and as a result stay passive.

Further findings particularly regarding performance measurement in SMEs have shown a rather high failure rate when it comes to implementations [44]. Mostly the characteristics mentioned above were held responsible for failing. However, performance measurement models which were developed for SMEs in the last two decades have shown a rather process-oriented focus as well as a stronger orientation towards stakeholder needs [9]. With respect to the objective of this thesis to provide a tool for facilitating resource efficiency improvement, the characteristics about SMEs found in literature confirm the original motivation of the main objective stated in chapter 1. Since SMEs lack resources, an improvement in resource efficiency can be assumed to be beneficial. There also seems to be a trend towards a somewhat process-oriented focus, which could favor the measurement of resource efficiency in manufacturing. Though, difficulties might occur in implementation and acceptance due to the fact that processes are less formalized in SMEs and behavior is rather passive.
2.3 The problem of analyzing resource efficiency

When looking for savings in the field of resources, the main focus is mostly put on reducing the consumption of physical resources. This means lowering expenses regarding transformed resources like material or energy. But only focusing on those ‘direct savings’ leaves the impact physical savings have on connected operation systems unconsidered [7]. Saving transformed resources in a process might also save transforming resources which act upon the former ones. Interrelations of resource utilization within the production system might not be obvious at first sight. To make this problem more evident internal effects of the 5 performance objectives, which have been discussed previously in this chapter, have been detailed further based on Slack et al. [15] in Figure 12.

| Quality: Error free parts | → reduces cost  
|                         | → increases dependability |
| Speed: Fast throughput   | → reduces inventories  
|                         | → reduces risk       |
| Dependability: Reliable operation | → saves time  
|                          | → saves money   |
| Flexibility: Ability to change | → speeds up response  
|                               | → saves time  
|                               | → maintains dependability |
| Cost: High total productivity | → direct influence:  
|                              | transformed resources (e.g. material)  
|                                | transforming resources (e.g. staff) |

Figure 12: Internal influences of performance objectives

As previously concluded, cost can be seen as a measure that indicates how efficient resources have been used. So, when it comes to the point of identifying what saved resource actually has caused a decrease in cost, clear allocations might become difficult. Referring to Figure 12, beyond financial savings the omission of physical resources has additional impacts. These impacts might influence nearby operations which again can result in savings. Material savings e.g. might lower the need of ancillary devices or result in lower expenses in logistics, which again might lower personnel cost, needed space for inventory or speed, which therefore again lessens the need for space. According to Schmidt et al. sometimes even planned invests for new machines can be rejected due to high savings that have not been anticipated before in resource efficiency projects [7].
Altogether, there is a possibility of those so called ‘hidden costs’ to exceed the ‘direct savings’ mentioned in the beginning of this section. Figure 13 depicts this problem in an iceberg model, which illustrates the visible directs cost, but leaves greater cost hidden below sea level [7].

![Figure 13: Direct cost and hidden cost of resource efficiency potentials](image)

In order to quantify hidden cost, a detailed examination of the production system is needed. The extent of the hidden cost then depends on the complexity of the examined production system. Different types of waste can be embedded in, or related to each other [27] in such a way that consequences of resource savings remain ‘invisible’. Therefore additional information is needed that mostly can only be obtained on-site. This information may, for instance, be related to organizational aspects, applied technologies, size of machines, product specifications, batch sizes or resource prices. The understanding of how those aspects are related to each other makes it possible to clearly estimate the extent of hidden cost savings. Consequently, detailed analyses and comprehensive specialized knowledge is necessary in order to finally grasp the complexity of the production system and identify all direct as well as all hidden cost. Hence, potentials concerning resource efficiency are difficult to identify, but might eventually be rewarded with great savings.
2.4 Summary

Resource efficiency deals with the utilization of resources, i.e. how well transformed and transforming resources are utilized in manufacturing in order to achieve a desired outcome. In doing so, economical as well as ecological objectives are considered. Within this scope waste not only includes non value-adding activities in terms of lean management, but furthermore any unnecessary use of resources and releases to environment. Additionally, the reutilization of waste can be seen as a resource.

Although in theory the concept of resource efficiency and productivity might be conflicting in some points, environmental progress does not necessarily go along with a loss of economical benefits in practice. However, the extent to which ecological aspects are considered within an organization needs to be decided by the management and put in context of an organization’s strategic objectives. This can be supported by proper design and alignment of performance measures. Performance measures quantify the efficiency or the effectiveness of an action and support decision-making. When designing performance measures, various recommendations should be considered in order to ensure appropriateness. Major attention should be given to the behavior which is induced by a measure when implemented as well as the avoidance of one-dimensional focus.

The less formalized processes and typically reactive behavior of SMEs might complicate implementations or application processes of new measures. But since there usually is a lack of resources in SMEs, it can be assumed that improving resource efficiency is quite beneficial for the overall situation of SMEs. Still, SMEs have special characteristics that differentiate them from large companies and need to be considered.

One general issue when identifying saving regarding resources is the problem of hidden potentials. Depending on the complexity of the individual production system, different types of waste can be embedded in a non-transparent manner. In order to reveal hidden potentials, special knowledge and detailed on-site analyses are necessary to grasp all interrelations within the production system. This effort might be rewarded with extraordinary amounts of savings, which might have not been anticipated before.
3 Research approach

Given the summary of the previous chapter, further delimitations are possible. The literature review revealed that resource efficiency must be aligned to the long-term goals of an organization. Since the main objective of this thesis is to support various SMEs from a general point of view, individual solutions are not likely to be feasible. Accordingly, alignment to strategy and relevance of resource efficiency within an organization cannot be determined by the tool. These tasks are expected to be done by the management. Likewise analyses of production systems in order to grasp the complexity of interrelated resources to reveal hidden potentials cannot be provided since detailed on-site information is needed. Hence, a tool can rather be supportive in displaying the current efficiency in manufacturing while using appropriate measures and therefore drawing attention and to the topic of resource efficiency. For this purpose a quite general collection of resource efficiency measures is needed in order to cover preferably all resources. At the same time a tool has to be applicable to any kind of SME independent from industry. So at this point, there are two research questions that can be raised.

Research question 1: What are appropriate measures for quantifying resource efficiency?

Research question 2: How can applicability of a computer-based tool be ensured for various SMEs in different manufacturing industries?

The first research question is covered in chapter 4 and deals with the design of resource efficiency measures for different kinds of resources. This means various measures will be defined based to the current state of knowledge to get a preferably complete picture about resource utilization in manufacturing. The answer of this question is given at the end of the chapter.

The second research question addresses issues concerning the special characteristics of SMEs and is treated in chapter 5. Due to a variety of businesses and inconsistency of structured approaches, a more detailed study about the internal situations of SMEs and their daily operations is necessary for addressing resource efficiency issues. Since this part of the thesis deals with a set of contemporary events which the investigator is not able to ma-
a case study research is carried out in four SMEs according to the case study design of Yin [45]. This case study approach consists of five steps:

1. A study’s question
2. Its propositions
3. Its unit of analysis
4. The logic linking the data to the propositions
5. The criteria for interpreting the findings

1. Formulating a study question: A research question of proper form and substance has to be formulated. For case studies the most appropriate questions are “how” and “why” questions.

2. Formulating study propositions: Based on the previous study question, propositions have to be made to determine what exactly should be examined within the scope of study. Every proposition has one focus that should be analyzed within the study question.

3. Identifying unit of analysis: The unit of analysis is a definition of what the actual “case” is. It defines beginning and end point of the respective case. The unit of analysis must clearly be distinguished from other units which are not included in study. Furthermore time boundaries and limits of data collection have to be specified. Previous research in the respective fields is suitable for comparing findings.

4. Linking data to propositions: After investigation and data collection, pieces of information may be related to some theoretical proposition. The goal is to match the collected data to a certain pattern.

5. Criteria for interpreting a study’s findings: The previously found patterns will be analyzed in order to identify sufficiently contrasting patterns. At least two rival positions are necessary in order to interpret findings.

At the end of this chapter the second research question is answered.
The results of both investigations then serve as basis for the actual development of a computer-based tool. Figure 14 illustrates the entire approach from problem description until final solution.

Figure 14: Research approach
4 Development of resource efficiency measures

In this chapter, different types of measures are designed within the scope of resource efficiency in order to answer research question 1, which has been formulated in the previous chapter as: *What are appropriate measures for quantifying resource efficiency?*

To avoid one-dimensional focus, a balanced set of measures has to be designed which covers transformed and transforming resources from various perspectives. Consequently, measures are designed within the following fields, which are arranged in alphabetical order:

- Energy
- Environment
- Human resources
- Logistics
- Machining and manual activities
- Material
- Quality

With regard to performance objectives from chapter 2, energy and material are directly cost-related while machining, manual activities and logistics cover dependability, flexibility and speed. Quality is measured separately. Since resource efficiency is also dealing with impacts operations have on nature, the environmental perspective is also included. Likewise employees are taken into account in terms of human resources.

4.1 Designing measures

Since the main objective is the improvement of resource efficiency, measures should stimulate improvement in the first place. One way of reflecting the performance of an operation is to design a measure which relates measured values of an operation to its theoretical optimum \[28\] \[46\]. That way the current performance of an operation is measured against a target value. Depending on if the value needs to be minimized or maximized one of the following equations can be used:
\[
\begin{align*}
\text{PM}_{\text{MIN}} &= \frac{\text{targeted value [unit]}}{\text{measured value [unit]}} \% \quad (4.1) \\
\text{PM}_{\text{MAX}} &= \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \% \quad (4.2)
\end{align*}
\]

where

PM\text{MAX}, PM\text{MIN} = \text{The value of the performance measure [%]}

Using this type of measure enables clear quantification of potentials and therefore stimulates improvement. Also, this ratio is easily understood by all staff. Overall comparisons in terms of benchmarking are facilitated as well. It is important to note that each measure only covers one dimension. These basic equations are used in the following subsections in order to quantify the degree of resource utilization. The criterion for identifying the theoretical optimum of consumption is the value-adding criterion. Using the value-adding fractions of resource consumption enables the identification of unnecessary resource use.

4.1.1 Energy

In order to design a measure for energy efficiency, energy consumption during manufacturing processes needs to be measured. Then value-adding processes and their specific energy consumption have to be identified. Figure 15 depicts the general model of energy consumption in manufacturing based on Erlach [4] and Müller [3].

![Figure 15: General model of energy consumption of a single operator in a manufacturing plant](image-url)
The total energy consumption is represented by the area beneath the load curve. A load curve consists of measuring points which are in a chronological order. The load curve in Figure 15 shows the consumption of one operator in a manufacturing plant. In this model the total consumption can be divided into three components:

- Standby consumption of the plant
- Standby consumption of the operating unit
- Consumption of the machining cycle

The standby consumption of the plant describes the amount of energy that is consumed outside of the planned production time, i.e. on weekends when machines are turned off. The standby consumption of the operating unit is the amount of energy that is consumed during idle times of machines. It can usually be measured when the machines are not operating but switched on.

The consumption of the machining cycles is that particular fraction of the total consumption which actually adds value to the customer. Machining cycles are defined as the time period a machine needs in order to process a part or a batch. Relating the consumption of machining cycles to the total consumption within a defined time period indicates how efficient energy has been used in order to serve customer needs. The consumption during machining cycles therefore serves as theoretical optimum. Hence, the equation for energy efficiency can be formulated as shown in equation 4.3.

\[
PM_{MIN} = \frac{\text{targeted value}}{\text{measured value}} \times 100\% = \frac{\text{machining cycle}[\text{kWh}]}{\text{total consumption}[\text{kWh}]} \times 100\% = \text{Energy efficiency} \quad (4.3)
\]

Identifying necessary fractions of consumption in order to calculate this measure can be quite extensive when starting from plant level, since the load curve represents the sum of all consumptions inside the building. One way to approach this problem is given by Müller [3]. Value-adding fractions of consumption can be identified and allocated by using a top-down approach. Starting with the entire plant and breaking down the total amount of consumed energy into smaller fractions according to the levels of the plant enables allocating energy consumption to the corresponding consumer in a stepwise manner. Since a performance measure is successful when the benefit by using it exceeds the cost from measuring
it [28], an organization’s cost of identifying data using this approach depends on the plant and its layout.

4.1.2 Environment

Since ecological aspects belong to the concept of resource efficient manufacturing, environmental impacts need to be taken into account as well. Environmental impacts consist of the amount of resources taken from nature and the release during and after the manufacturing process. The former impact is covered by most of the other measures in this chapter using the value-adding criteria to identify unnecessary resource use. The latter impact regarding releases needs to be defined yet. In detail that means it is necessary to identify what emissions are released to air, water and soil [12]. Until now, the procedure of designing measures has been based on calculating efficiency by relating an optimum value to a measured value. When discussing environmental impacts apart from the economical interests, the optimum regarding environmental impacts is zero. So preferably there should not be any impact at all. Obviously this is not a realistic solution. One approach for solving this problem might be setting a threshold regarding emissions. That threshold could, for instance, be based on discussions with stakeholder groups. For now environmental releases shall be measured in their absolute amount as a temporary solution. Since it gets attention what gets measured, emissions can be tracked this way in order to draw attention to environmental impacts.

4.1.3 Human resources

Dealing with individuals in an organization includes social aspects during manufacturing processes. Since it is not easy to retrieve quantitative information about social circumstances, safety is measured indirectly as indication for efficient use of human resources. For this purpose health rate is defined as number of days attended to work divided by the total number of work days during a defined time period.

\[
PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \times \frac{\text{Number of attended days [days]}}{\text{Total number of working days [days]}} \times 100 \% = \text{Health rate} \quad (4.4)
\]
The amount of days not attended due to sick-leave can be taken as indicator towards working environment or social circumstances.

4.1.4 Logistics
The main objective of logistics is to provide the right materials and products, at the right time, to the right place, in the right quality and quantity at minimum cost [47]. Logistics rather reflect an overall view on an organization’s performance since processes between manufacturing steps are considered. Main objectives regarding logistics consist of delivery time, variance of scheduled delivery to actual delivery and dependability of delivery [48]. From this customer oriented perspective, internal objectives can be derived. For the purpose of supporting resource efficiency, internal order lead time and dependability of internal processes are of major concern at this point.

Order lead time is defined as time period one product needs to pass through all its manufacturing steps [49]. Hence, a measure can be defined which relates the sum of all process times of an order to the actual measured lead time of an order. Process time is defined as the time period one order stays within a manufacturing process. In this way the overall speed of a production system can be evaluated since also times between manufacturing processes are taken into account. Figure 16 pictures this concept.

![Figure 16: Concept of delivery speed for a single order](image)

Equation 4.5 shows the formula of calculating delivery speed.

\[
PM_{\text{MIN}} = \frac{\text{targeted value}}{\text{measured value}} \cdot \frac{\sum \text{Process time}[\text{time}]}{\text{Lead time}[\text{time}]} \cdot 100 = \text{Delivery speed}
\]  

(4.5)
Reliability within manufacturing is an indication about how stable internal processes run and therefore how well resources are coordinated. Comparing planned lead time to the actual lead time indicates if orders are delayed or speeded up. As a result variances regarding planned schedules can be used to analyze dependability. According to Lödding, dependability can be calculated as percentage of deliveries which have been on time in a defined time period [48]. Given thresholds for delayed and early orders, the share within upper and lower threshold represents dependable deliveries as depicted in Figure 17.

![Dependability of delivered orders](image)

Accordingly, dependability can be calculated as the number of orders within tolerance related to the total number of orders.

\[
PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \times \frac{\text{Number of orders } T_{\text{LOW}} \leq \text{within} \leq T_{\text{UP}}}{\text{Number of orders}} = \text{Dependability} \tag{4.6}
\]

So far a make-to-order production has been anticipated, which has left inventory unconsidered. Anytime inventory is stocked it implies that asset is unused and space and utilized manufacturing resources are occupied, which again causes cost. On the other hand, inventories facilitate to maintain a continuous production flow and also to get over failures during manufacturing and therefore enable accurate scheduling [47]. Since there are no value-adding processes involved in this rather management-related perspective of an organization, resource efficiency within inventory management is considered by calculating the rate of used room and inventory turnover. The former describes the amount of room that is ac-
tually used, while the latter indicates how well the actual space is utilized by calculating the turnover of the inventory. It therefore makes sense to use both measure in combination.

\[
PM_{\text{MIN}} = \frac{\text{targeted value [unit]} \times \%}{\text{measured value [unit]}} = \frac{\text{Volume of storage unit} \times \text{Number of units [m}^3]}{\text{Volume of total storage room [m}^3]} \times \% = \text{Rate of used room} \quad (4.7)
\]

The rate of used space considers how much room and therefore land is needed and how much of it is actually used.

\[
PM_{\text{MAX}} = \frac{\text{Outward stock movement [parts]} \div \text{Average stock [parts]}}{\text{Period}} = \text{Inventory turnover} \quad (4.8)
\]

Inventory turnover describes how many times the total inventory has been moved and replaced within a defined time period. It indicates to what extent inventory space is used and how fast products are moving apart from manufacturing processes.

### 4.1.5 Machining and manual activities

Generally, activities in manufacturing can be split up into (semi-)automatic activities and manual activities. Seeing time as a resource, time-based measures can be used for quantifying the performance of manufacturing processes. Time-based measures are easy to measure, easy to understand and also facilitate comparisons of manufacturing methods. Moreover, a linear relationship between money and time can be assumed [28]. One of the most spread measures for (semi-)automatic manufacturing processes is undoubtedly the overall equipment effectiveness ratio. It considers three aspects of performance [15]:

- **Availability:** Time the equipment is available to operate
- **Speed:** Throughput rate of the equipment
  (sometimes also referred to as ‘performance’)
- **Quality:** Quality of the produced products or services

Availability of a machine is calculated by relating the time a machine has actually been running to its planned production time. In this way down time losses are identified.

\[
PM_{\text{MAX}} = \frac{\text{measured value [unit]} \times \%}{\text{targeted value [unit]}} = \frac{\text{Operating time [time]}}{\text{Planned production time [time]}} \times \% = \text{Availability} \quad (4.9)
\]
The manufacturing speed of a running machine can be evaluated by dividing the net operating time by the operating time. Doing so, speed losses are identified which make the machine operate at less than the maximum speed.

\[
PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \% = \frac{\text{Net operating time [time]}}{\text{Operating time [time]}} \% = \text{Speed}
\]  
\[
(4.10)
\]

Finally, quality rate considers the amount of scrap parts and necessary rework time. The amount of time that is left over is called valuable operating time and divided by the net operating time. It is the main goal to maximize valuable operating time.

\[
PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \% = \frac{\text{Fully productive time [time]}}{\text{Net operating time [time]}} \% = \text{Quality}
\]  
\[
(4.11)
\]

Alternatively quality can also be calculated as ratio of good parts to total parts. This is discussed in one of the following sections. Figure 18 sums up how the elements of availability, speed and quality are related to each other [46].

\[
\text{Planned production time}
\]

\[
\text{Operating time}
\]

\[
\text{Downtime loss}
\]

\[
\text{Net operating time}
\]

\[
\text{Speed loss}
\]

\[
\text{Fully productive time}
\]

\[
\text{Quality loss}
\]

\[
\text{Figure 18: The concept of the overall equipment effectiveness}
\]

The overall effectiveness ratio measures both efficiency and effectiveness. Ability to change, a maximum throughput and proper quality are the main objectives of this measuring approach.
For manual activities a measure can be defined which quantifies the efficiency of workers in manufacturing. Seeing time as a resource, value-adding time can be related to the total time of attendance [50]. The amount of time used to benefit customers during attendance can be specified as percentage. Figure 19 pictures the idea along a time line.

![Figure 19: Concept of worker efficiency](image)

The formula is similar to the one from delivery speed, but is based on the total time of attendance of employees instead of order lead time. Worker efficiency can accordingly be calculated as shown in equation 4.12.

\[ PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \times \frac{\%}{\%} = \frac{\sum \text{Value-adding time [time]}}{\text{Total time of attendance [time]}} \times \% = \text{Worker efficiency} \quad (4.12) \]

It is generally quite challenging to find the ‘right’ measure for manual activities that as well induces appropriate behavior. Especially the use of value-adding time is a subjective concept [28] which in this case supports activities with long processing times. Again, it should be noted that measures solely based on time have limited informative value.

### 4.1.6 Material

Improving material efficiency saves energy and reduces the consumption of primary resources and reduces the volume of waste [51]. There are several approaches about how material efficiency can be increased [51]:

- good housekeeping
- material efficient product design
• material substitution or use of materials with improved properties
• product and material recycling
• decreasing inputs of primary materials

A measure should support these activities and assist in what approach is the most appropriate one for improvement activities. In terms of efficiency this means to measure how much of the initial material has actually been used. Unnecessary use of material can be quantified by relating the weight of the final product to the initial amount of material used up in the examined processes. Figure 20 describes the general concept of material consumption based on the idea that one fraction of raw material remains unused.

![Figure 20: Concept of material consumption](image)

The amount of material that has actually been processed to fulfill customer needs can then be used as shown in equation 4.13.

\[
PM_{\text{MIN}} = \frac{\text{targeted value}}{\text{measured value}} \times \frac{\text{weight product [kg]}}{\text{weight raw material [kg]}} \times 100\% = \text{Material efficiency} \quad (4.13)
\]

In order to calculate material efficiency in practice, the weight of the raw material has to be identified as well as the weight of the final product or unused material. Of course, this can be done for liquids in the same way.

4.1.7 Quality

Quality has already been discussed to some extent during the introduction of the overall equipment effectiveness. Nevertheless, it is still considered with a separate measure in this
subsection. Alternatively to what has already been discussed, quality can also be calculated as ratio of good parts to the total amount of produced parts.

\[ PM_{\text{MAX}} = \frac{\text{measured value [unit]}}{\text{targeted value [unit]}} \times 100\% = \frac{\text{Number of good parts [parts]}}{\text{Total number of parts [parts]}} \times 100\% = \text{Quality rate} \quad (4.14) \]

A quality rate of 100% means that all parts have been manufactured without errors. It is also an indication that resources have been bundled effectively, so a pay-off can be expected in future when the product is put on the market. If discarded, the product itself and the previously used up resources for processing the product can be regarded as waste. In terms of resource utilization this is not regarded as an efficient way of manufacturing. Hence, in order to know if processed resources have been used properly, one has to know if the output has been effective. Or to put it in Porter’s words: Assuring quality means ensuring quality of other activities [52].

4.2 Overview

The developed measures are summed up in a Table 1. Altogether there are 12 different resource efficiency measures.
It has been the intention to define a balanced set of measures that quantifies the use of transformed and transforming resources. But how many measures are really needed in order to make a set balanced? When looking at the measures in detail one can recognize a variety of measurement units that serve as a basis for calculating percentages. Power, weight, time, room, amount of parts and amount of orders make up the covered dimensions. At this point, the range of dimensions which have been covered is assumed to be sufficient for the purpose of quantifying resources efficiency in manufacturing.

So far it is not possible to make a general statement about relevance of each measure without having further information about the individual situation at the SME. This ‘pool’ of measures needs to be put into context in order to find out which measures are the most relevant ones. Additionally, it should be noted that these measures are lagging measures.

Table 1: Overview of resource efficiency measures

<table>
<thead>
<tr>
<th>Category</th>
<th>Name</th>
<th>Formula</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Energy efficiency</td>
<td>( \frac{\text{machining cycle [kWh]}}{\text{total consumption [kWh]}} )</td>
<td>%</td>
</tr>
<tr>
<td>Environment</td>
<td>Releases</td>
<td>( \text{Absolute amount of release (preferably with threshold)} )</td>
<td>unit</td>
</tr>
<tr>
<td>Human resources</td>
<td>Health rate</td>
<td>( \frac{\text{Number of attended days [days]}}{\text{Total number of working days [days]}} )</td>
<td>%</td>
</tr>
<tr>
<td>Logistics</td>
<td>Delivery speed</td>
<td>( \frac{\sum \text{Process times [time]}}{\text{Lead time [time]}} )</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Dependability</td>
<td>( \frac{\text{Number of orders} \leq T_{\text{off}} \leq T_{\text{up}}}{\text{Number of orders}} )</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Rate of used room</td>
<td>( \frac{\text{Volume of storage unit} \times \text{Number of units [m]}}{\text{Volume of total storage room [m]}} )</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Inventory turnover</td>
<td>( \frac{\text{Outward stock movement}}{\text{Average stock [parts]}} )</td>
<td>( \frac{\text{1 period}}{\text{period}} )</td>
</tr>
<tr>
<td>Machining</td>
<td>Availability</td>
<td>( \frac{\text{Operating time [time]}}{\text{Planned production time [time]}} )</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>( \frac{\text{Net operating time [time]}}{\text{Operating time [time]}} )</td>
<td>%</td>
</tr>
<tr>
<td>Manual activities</td>
<td>Worker efficiency</td>
<td>( \frac{\sum \text{Value - adding time [time]}}{\text{Total time of attendance [time]}} )</td>
<td>%</td>
</tr>
<tr>
<td>Material</td>
<td>Material efficiency</td>
<td>( \frac{\text{weight product [kg]}}{\text{weight raw material [kg]}} )</td>
<td>%</td>
</tr>
<tr>
<td>Quality</td>
<td>Quality rate</td>
<td>( \frac{\text{Number of good parts [parts]}}{\text{Total number of parts [parts]}} )</td>
<td>%</td>
</tr>
</tbody>
</table>
which describe outcomes from a retrospective. They indicate the amount of potential resource savings that can be realized if proper actions will be taken.

By now research question 1 can be answered, which has been stated at the beginning of this chapter as: *What are appropriate measures for quantifying resource efficiency?*

Quantifying resource efficiency can be achieved by relating measured values of resources to target values. In that way percentages for each single resource can be calculated that quantify how well resources have been used. Using the value-adding criterion to determine target values enables identifying unnecessary use of resources. Hence, improvement is stimulated by quantifying potentials of direct savings. This approach as well supports overall comparisons of different production lines. One-dimensional focus can be avoided since one operation can be quantified from different perspectives using various measures.

Taking into account environmental measures completes the scope of resource efficiency by measuring output in terms of releases to environment. As indicated above, these measures need to be put in context of an organization in order to find out the degree of individual appropriateness.
5 Case study research in small and medium-sized enterprises

Since the goal of the thesis is to support particularly SMEs whose characteristics might hinder successful implementations, a representative sample of 4 SMEs from different industries has been examined more closely. The question that serves as a basis for this investigation is research question 2: *How can applicability of a computer-based tool be ensured for various SMEs in different manufacturing industries?*

As stated before, research questions that begin with “how” or “why” and focus on contemporary events, which the investigator is not able to manipulate, are suitable for case studies [45]. The case study carried out in this chapter is based on Robert Yin’s case study research approach. As the general approach has already been introduced in chapter 3 of this thesis, the 5 steps for conducting a case study are directly applied in the following sections.

5.1 Formulation of a study question

Since the research question is the initiator of this case study, the research question serves as study question:

How can applicability of a computer-based tool be ensured for various SMEs in different manufacturing businesses?

5.2 Formulation of study propositions

Based on the previous study question, propositions have to be formulated to determine what exactly should be examined within the scope of study. In order to derive study propositions, the meaning of ‘applicability’ has to be specified. A follow up question to specify the term applicability can be: At what point is something applicable to SMEs? Or more precisely: Under what circumstances will SMEs actively use a computer-based tool?

At this moment, arbitrary suggestions are made in order to find study propositions. It is assumed that two terms might facilitate finding an answer about applicability in SMEs: A computer-based tool will is applicable when it deals with *relevant* issues in an *appropriate* manner. Consequently, there are two derived study propositions:
• What is relevant to SMEs?
• What is appropriate to SMEs?

Surely these two questions still do not exactly declare what should be examined in detail, but it narrows down the quite wide term of ‘applicability’ to two single aspects.

Assuming that it gets only measured what is regarded as important, one possibility to find out what is ‘relevant’ can be the definition of currently used measures in manufacturing. Checking SMEs for measures make investigations quite simple since criteria are put into numbers. On the other hand this assumption might also be misleading since SMEs tend to have rather unstructured approaches as discussed in chapter 2. Another convenient way to obtain information about relevance is carrying out personal interviews. Additionally to checking current measures, using interviews is an extra way to retrieve more and maybe more proper information about the focus of the respective SME.

In order to evaluate appropriateness of an action, criteria must be defined that reflect information about benefit and cost. It is assumed that as long as benefit exceeds cost, action will be regarded as appropriate in terms of its applicability. Since the result from the assessment of resource efficiency can be seen as the main benefit, the effort it takes to achieve this goal can be seen as cost. With regard to a computer-based tool and resource efficiency measures 2 criteria are feasible: Technical appropriateness and content-related appropriateness. The former deals with the technical requirements, while the latter focuses on the information within the system. The content-related investigation can be limited to the measures developed in the previous chapter.

Finally there are 2 questions to answer in order to evaluate appropriateness:
• What computer systems are in use?
• What kind of data is available regarding energy, material, machining and assembly, logistics, quality, environment and human resources?

Figure 21 gives an overview of the study propositions which have been discussed so far.
5.3 Definition of the unit of analysis

During this step the actual “case” has to be defined as well as a clear beginning and end point. Furthermore, time boundaries and limits of data collection have to be specified. Since the topic of interest is about ensuring applicability in manufacturing SMEs, a section of the shop floor area which includes manufacturing processes as well as management activities would be a proper “case”. Hence, the unit of analysis can be defined as subareas of manufacturing factories which contain value-adding processes and measures for management activities.

There are 4 SMEs participating in this case study. The investigation for each SME lasts 1-2 days, depending on individual situation of the SME. All 4 study propositions will serve as a basis for questionnaires during the investigation. The used questionnaires are attached in appendix 1. In the upcoming sections, the collected data is discussed.

5.4 Relation of obtained data and propositions

In order to find out what is relevant to SMEs, personal interviews with the management have been carried out as well as used measures reviewed. In this section obtained data is linked to the study propositions.
5.4.1 Relevant aspects

Given the result of all interviews, resource efficiency is not seen as an unimportant topic from the management’s perspective, but it clearly is not perceived in terms of improving the ecological situation. Figure 22 shows an extract of the total results. Multiple choice questions as well as open questions have been used during the interview. The complete questionnaire can be found in appendix 1.

All 4 SMEs declared resource efficiency to be a purely economical problem. Hence, the main focus of SMEs is put on economical aspects, i.e. savings in the course of reducing input consumption and therefore cost. From an overall perspective cost is anticipated as the greatest problem in terms of resource efficiency, followed by consumption and customer relevance as shown by the right hand graph in Figure 22. Ecological consequences concerning releases to environment are not regarded as major problems.

Furthermore, SMEs have the highest demand regarding support is in the area of data collection and consulting. This matches the typical characteristics of SMEs discussed in chapter 2. Tacit knowledge and a lack of resources for data handling seem to be obstacles to resource efficiency improvement.

If asked what kinds of actions have been taken in the past in order to improve resource efficiency in manufacturing, mostly lean management approaches have been mentioned. This confirms a rather economical oriented understanding of resource efficiency. The effects of those improvement approaches often resulted in more work regarding data handling. Additionally, waste is perceived as a resource only in combination with financial benefits.
During the interview one quite special task was given to the managers. He or she had to rank measures with respect to their relevance by placing notes with the measure’s name written on within the two extremes statements ‘relevant’ and ‘not relevant’. The result is illustrated in Figure 23, which shows every SME’s evaluation regarding relevance of measures.

![Figure 23: Relevance of measures in SMEs](image)

Measures focusing on machining, assembly and logistics are consistently rated as the most relevant ones. Material, energy, staff and environment vary in terms of relevance. Since SMEs from different industries with different products have been examined it is quite logical that there is a varying perception about relevance regarding resources and environment. One striking fact when looking at Figure 23 though is that quality and measures related to machining and assembly are throughout rated as the most relevant ones. Since measures about machining, assembly and logistics have mostly been time-based, it can be stated that quality and time are, the most important criteria for SMEs, independently from industry. Obviously SMEs that operate lots of cutting processes might rate material issues as more relevant than other resources. In the same way human resource has been rated higher by the management if there has been more manual activity in manufacturing. Also environmental impacts have only been measured since it was required by law in order to track hazardous substances. This again indicates a minor importance regarding ecological aspects.
Measures that have been reviewed in SMEs are shown in Figure 24.

![Number of used measures in manufacturing](image1)

![Shares of used measures in manufacturing](image2)

*Figure 24: Extract of case study: Used measures in manufacturing SMEs*

The graph on the left hand side shows the number of measures used by each SME in manufacturing. These measures have either been found on a bulletin board in production or used by the responsible manager. The right hand graph shows a pie chart of the same sample, based on the cumulated amount of measures found in the SMEs. Most measures are used in the fields of machining, assembly and quality. Together they make up roughly 70% of all examined measures. This very well matches the managers’ statement from the previous analysis, which indicated a predominance of time-based and quality measures. What catches the eye though is that material has been rated as quite relevant by some SMEs as shown in Figure 23, but no SME has intentionally defined a measure regarding material and used it in daily manufacturing.

Altogether, it seems that most focus is put on time-related and quality issues. Resources vary in relevance. Referring to the three objectives for improving resource efficiency discussed in chapter 2, the objective ‘reducing emissions’ is out of scope with respect to the examined SMEs. There is no motivation to actively approach the environmental side of manufacturing processes. Hence, resource efficiency seems to be quite limited to the economical aspect. Furthermore, SMEs demand most support in the field of external know-how and support in data collection.

### 5.4.2 Appropriate aspects

Computer systems in the examined SMEs are inconsistent. There is a high variation of enterprise resource planning systems and individual solutions when it comes to informa-
tion processes in manufacturing. Also the data format varies within single SMEs. From the technical point of view, no particular computer system can serve as a common basis for processing data. Similarly as for computer systems, availability of data which is needed in order to quantify resource efficiency measures is inconsistent as shown in Figure 25. The data in Figure 25 has been calculated using a check list which is based on the measures designed in chapter 4. An availability of 100% means that all necessary components have been found in the SME in order to calculate that particular measure.

![Available data for calculating resource efficiency measures](image)

*Figure 25: Extract of case study: Availability of data for calculating measures*

Every SME tracks information regarding human resources. Also quality data is available at every SME in a complete manner. The remaining measures can only be calculated if additional data is collected. This has to be done to an individually different extend. The only data that can be taken for granted is quality data and human resource data.

All in all, there is no consistent picture concerning used computer systems and data availability. Given the fact that SMEs also lack capital and human resources, a supporting tool should not only come from the lowest degree of common standards, but also use as few resources as possible. That way also SMEs with the least advanced computer infrastructure and lowest amount of data are able to usefully apply a tool. To put it in other words: Pareto optimality must be reached, i.e. no SME shall be handicapped because of another SME. Hence, a platform must be chosen that represents the lowest common background. A disadvantage resulting from this approach is a low individual fitment for each SME. Although
it is aimed for an efficient solution, the tool might not necessarily fit the individual technical environment of every single SME. Given the main objective of this thesis, i.e. to provide a generally applicable tool to support a group of SMEs, individual adjustment cannot be reached per se due to the nature of the objective. Every SME therefore has to make own investigations in order to ‘learn’ how to apply this tool and adjust it to its own internal infrastructure. The effort of learning though, which is also resource consuming, can be minimized by a proper design of the tool and its user interfaces. This is discussed in the next chapter.

5.5 Criteria for interpreting the study’s findings

So far the study revealed that focusing on economical issues, primarily based on quality and time measures, while keeping the lowest common background regarding computer systems and data level is the most likely way to succeed when developing a tool for SMEs. This section tries to identify the cause for this outcome.

One possible explanation of that rather economical focus of SMEs can result from a different understanding of what resource efficiency means. The term has been defined in chapter 2 and as well been connected to 3 objectives. Those 3 objectives clearly link economical to ecological issues. But what if the interviewees, who did not have a theoretical clarification about this, have a different perception of what resource efficiency means? Managers might weight those objectives differently or they might not even be aware of them. Since the level of knowledge has not been considered in the interviews and is therefore treated as equal among all participants, the objective ‘reducing consumption of resources’ seems to be the most likely one to be perceived by managers. This clearly matches the resulting statistics regarding perception of resource efficiency and its expected challenges which have been discussed in the previous sections.

Another argument about SMEs is their characteristics, which have been introduced in chapter 2. SMEs are lacking human and capital resources and just want to ‘get the job done’ while struggling to survive. This explains that much attention from the management is given to time-based measures. There is no time left for additional issues that do not directly benefit the SME’s financial situation.
On the other hand, if resources are scarce in SMEs it is questionable why the use of material measures is throughout neglected by the management. As already mentioned, none of the SMEs has defined measures to track material issues (see Figure 24), although material has been rated quite relevant and data has been available in many cases (see Figures 23 and 25). As stated in the introduction, material cost represents the largest share of the overall cost in manufacturing. SMEs can increase their operating profit margin much easier by reducing material cost than by increasing sales [53]. Surely it has to be specified what kind of material is actually processed to exactly determine potentials, but simply from the management point of view there seems to be no need to take material issues into account. Consequently, there are potentials existing which remain untouched. Thinking in terms of monetary values, financial savings could be generated which create room for decisions, e.g. regarding additional resources. Hence, the argument of SMEs lacking resources does not seem to fit in this case study since it can be outweighed using the argument of unrealized saving potentials.

SMEs are further known for having tacit knowledge, less formalized processes and few managerial capacities. This indicates a lack of knowledge in managing processes and applying methodologies. Indeed, the SMEs declared that, besides needed support in data acquisition, there is high demand for consulting (see appendix 1). This shows that there is awareness about a lack of structured approaches within the SMEs as well as a need to change this. Administrative activities are simply neglected since major attention is given to daily business. This goes along very well with the inconsistency of used computer systems and data formats found within SMEs.

As a result it can be assumed that a lack of know-how regarding resource efficiency and management approaches is the reason for a rather economical focus respectively for unrealized potentials.

By now research question 2 can be answered, which has been stated at the beginning of this chapter as: How can applicability of a computer-based tool be ensured for various SMEs in different manufacturing businesses?

Given the result of the case study, applicability of a computer-based tool for various SMEs in different manufacturing businesses can be ensured by meeting the following requirements:
• Keep daily business in focus and especially time and quality as the most important issues independent from industry; further resources need to be considered as well but might vary in relevance
• Meet lowest common requirements regarding computer programs and consider the fact that there is hardly any data available
• Provide know-how regarding resource efficiency and ensure easy use of the tool
6  Development of a computer-based tool for consistent assessment of resource efficiency

In the previous chapters, resource efficiency, performance measures as well as characteristics of SMEs have been discussed (chapter 2). Accordingly, resource efficiency measures have been developed (chapter 4). Further preparatory work has been carried out in chapter 5 in order to learn about applicability in SMEs. The essential part of the thesis is discussed in this chapter. A computer-based tool is developed which is based on 3 fundamental pillars. The first one focuses on evaluating the relevance of resource efficiency measures for any single SME. In order to achieve this, previously defined measures are classified and ranked. The second pillar deals with the actual program. A proper platform will be chosen and the structure of the tool as well as its interfaces is designed. The third pillar consists of a description of steps for assessing resource efficiency. The goal is to ensure a proper and consistent assessment approach. Figure 26 shows a symbolic picture of the entire concept. Based on 3 pillars a computer-based tool is developed using the previously developed resource efficiency measures and the results from the case study.

Figure 26: Development of a tool for consistent assessment of resource efficiency
6.1 Development of a ranking method

In chapter 4, 12 measures have been designed for quantifying resource efficiency. Those measures serve as a basis for each SME in the assessment of resource efficiency. In order to put this quite general pool of 12 measures into context of SMEs, a ranking method is developed in this section which supports the prioritization of measures with respect to resource efficiency. The development of a ranking method can be split-up in two elements.

- Classification of resource efficiency measures
- Design of an evaluation method

6.1.1 Classification of resource efficiency measures

In this subsection resource efficiency measures are classified. In order to classify resource efficiency measures, criteria have to be found which enable a grouping of resource measures in manufacturing industry. Since resource consumption is generally tied to different kinds of action, activity-based criteria are used. According to Porter there are 3 basic types of activities that every company has within any industry [52]:

- Direct activities
- Indirect activities
- Quality assurance

**Direct activities**

Direct activities are activities which directly add value to the customer and are therefore essential for ensuring income. In manufacturing those activities mainly consist of machining and assembly activities. In this thesis direct activities have been referred to as value-adding activities.

**Indirect activities**

These activities enable direct activities to run continuously. Among others, maintenance or operating facilities belong to these activities.

**Quality assurance**

This activity ensures the quality of other activities. Practically, this means monitoring, reviewing or reworking actions. As already discussed, quality measures are output related.
Now that criteria have been defined, resource efficiency measures can be classified and grouped. According to the previous criteria, there are 3 groups of measures resulting:

- Measures for value-adding resources
- Measures for organizational resources
- Measures for quality assurance

Figure 27 sums up current results and shows how all 12 resource efficiency measures have been grouped according to the type of activity.

Value-adding resources
This group of measures consists of energy efficiency, material efficiency, worker efficiency as well as availability and speed of machines. These measures describe resources that are directly consumed when adding value to the customer. Accordingly, the basic measurement units are power, weight and time. Since it is not obvious to what extent each resource in this group is used during a manufacturing activity, further information about the manufacturing process is necessary.
**Organizational resources**

Measures regarding logistics, environment and human resources represent this group. Logistics measures can be split up further into measures that rather focus on material flow, i.e. speed and dependability and measures for inventory management, i.e. degree of used space and inventory turnover. These measures describe what happens apart from the value-adding processes in manufacturing.

**Quality inspection**

The effectiveness of a manufacturing process is measured by quality rate. It is the only measure in this group.

As also indicated in Figure 27, the use of each of these measures is further specified. There are measures which can be regarded as ‘basic’ for the purpose of assessing resource efficiency. This group consists of quality rate, dependability, delivery speed and health rate. These measures are definitely necessary to assess what happens in between of the value-adding processes. There are also measures which can rather be seen as ‘optional’ due to different types of production systems. As, for instance, not every SME necessarily has inventory, a basic use of inventory turnover and rate of used room is not regarded as reasonable. Also environmental issues are rather optional since SMEs only measure their emissions when required by law. The use of value-adding resource measures though is quite specific and depends on what kind of manufacturing processes are actually examined and how these processes are designed. In order to bring a systematic order into this group of measures, the next subsection copes with the task to design a method to rank value-adding resource measures.

### 6.1.2 Design of an evaluation method for value-adding resources

In the last subsection resource efficiency measures have been classified. In this subsection an evaluation method is designed to enable a systematic ranking of value-adding measures. The objective is to support the identification of improvement potentials.

In order to enable a systematic ranking, a value benefit analysis is applied at this point. Value benefit analyses are known as multidimensional, semi-quantitative evaluation method, which has been named by several authors [54] [55] [56]. Generally, this method
enables evaluations and comparisons of different possible choices according to criteria, which have been selected subjectively. The entire evaluation method is not introduced at this point. Based on Zangemeister and Bechman, the procedure normally consists of 5 steps from which a compacted version of 3 steps is directly applied to this part of the development concept. These 3 steps are illustrated in Figure 28.

*Figure 28: Procedure of the value benefit analysis*

**Step 1: Setting up a hierarchy of objectives**

The objective of this approach is to rank measures focusing on value-adding resources. In order to achieve this, criteria need to be found that enable a proper ranking. Since this thesis aims at providing a general applicable tool, criteria need to be general as well. At the same time the chosen criteria ought to be distinguishable. Since value-adding resources are consumed during manufacturing, a standard for manufacturing processes is regarded as the most appropriate criteria for this purpose. The advantage of using a standard is a common and scientific background regarding all possible manufacturing processes, which enables handling the variety of processes within all SMEs. The standard DIN 8580 sums up manufacturing processes in which products are made from any physical materials [57]. As shown in Figure 29, manufacturing processes are divided into 6 main groups which can be broken down further [58].
Figure 29: Main groups of manufacturing processes according to DIN 8580

Table 6 presents short definitions of the 6 main manufacturing process groups (translated with support of The National Academies Press [59]).

<table>
<thead>
<tr>
<th>Phase-Change processes</th>
<th>Processes which produce a solid part from liquid material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation processes</td>
<td>Processes causing lasting deformations, but keep the volume of the part unchanged</td>
</tr>
<tr>
<td>Mass-Change processes</td>
<td>Processes which are characterized by the removal of material</td>
</tr>
<tr>
<td>Consolidation processes</td>
<td>Assembly of smaller objects into a single product</td>
</tr>
<tr>
<td>Coating process</td>
<td>Application of an adhesive layer of formless material to a work piece</td>
</tr>
<tr>
<td>Structure-Change processes</td>
<td>Processes which alter mechanical properties of an engineering material</td>
</tr>
</tbody>
</table>

Table 2: Definitions of 6 main manufacturing process groups

At this point the named manufacturing processes are not detailed further since the definitions of the main groups enable a clear distinction among processes on operational levels. The final hierarchy of objectives based on the manufacturing standard is depicted in Figure 30.
**Step 2: Weighting criteria**

After criteria have been defined, each of them has to be weighted in the next step according to their influence on the objective. A sum of 100% needs to be distributed across all manufacturing processes. Contrary to the ordinary procedure, this is done with respect to each value-adding measure at this point. This means 100% of each resource will be distributed to the manufacturing processes. The distribution of the percentages is handled in a subjective manner and describes the extent to which a manufacturing process is influencing the according value-adding measure. It should be noted that these weights do not clearly reflect reality. Furthermore, a perfect weighting is not achievable due to the high variety of manufacturing processes and other criteria which have been left unconsidered. At this point, a group discussion with experts from each SME would be a useful way to decide about the distribution of weights for the group of all participating SMEs. Since there has not been any group discussion, assumptions are made regarding the weights. A deformation process, for instance, which naturally causes no clippings, has a lower significance regarding material efficiency than a cutting process. Hence, the former gets a lower weight regarding material efficiency. If added up across all manufacturing processes, the sum of all weights has to result in 100%. For energy and material the procedure is likewise. In contrast, worker efficiency and availability/speed of machines are mutually exclusive, i.e. value-adding activities can either be done by machining operators or manually. It is assumed that the type of process does not influence process speed, which is why both time-related measures are weighted equally in every manufacturing process. Figure 31 outlines all weights.
Step 3: Creating a scale and calculating the ranking

Normally a scale needs to be defined at this point. Given several alternatives to choose from, this scale is usually used to characterize the degree to which every possible alternative is contributing to achievement of the main objective. This can, for instance, be done by defining a metric scale with defined maximum and minimum values.

In this particular case, there is no clearly defined scale as proposed by literature. In order to enable this ranking method to be applicable to all kinds of production systems, the quantity of examined manufacturing processes is serving as scale. Each examined manufacturing processes will be assigned to the according main group of the previously introduced standard. The total number of manufacturing process within each main group is then multiplied with the corresponding weights and added up for each resource.

If, for instance, there are only 2 cutting processes to be examined, the manufacturing group ‘Mass-Change process’ is rated with 2 while the other processes are rated with 0. Figure 32 shows how the ranking is calculated in this example. According to this model, the resource measure with the highest rank can be regarded as the most relevant one within the examined manufacturing processes.
Using this type of ‘flexible scale’ ensures applicability to every SME and every individual situation in manufacturing. Also, any number of manufacturing processes can be used to rank value-adding resources. Although this method enables systematic decision-making in a comprehensible and flexible way, there are limitations which need to be considered when using this method.

The only criterion that is taken into account when ranking value-adding measures is the type of manufacturing process. Other criteria that influence resource consumption, like technology, product design, batch sizes, dimensioning of machines or resource prices are not considered in this evaluation. Additionally, the weighting of each resource is based on subjective notions. It is therefore necessary to carefully reflect the result and its meaning. Hence, this evaluation method can only be seen as decision-making support, but not as final solution in a decision-making process.

6.2 Development of a software program

In this subsection the actual software program is developed. Starting with general conditions, technical and content-related aspects are discussed. Based on this discussion requirements are derived and likewise a proper software platform selected. Afterwards, the user interface is designed which gives the software its final look.
6.2.1 General conditions

The case study has shown that there are several restrictions that need to be considered when designing a tool. These restrictions can either be related to technical aspects or related to the content of the tool, which are both discussed in this subsection.

Technical restrictions are given by the SMEs and their specific environment in which a tool is supposed to operate. As the case study has shown, a computer system within the examined SMEs must meet the lowest common requirements. But what does that mean in terms of technical requirements? One important technical condition that needs to be considered is the environment in which the program operates in and its interfaces to other devices or programs. The initial situation at SMEs has revealed that there is no common set of interfaces existing that could be useful for the purpose of accessing internal information in order to assess resource efficiency. Even given the idea that collecting data from the SME’s environment was possible, the variety of data formats which exist within a single SME could not be covered. Furthermore, the information infrastructures which have been observed during case study were quite individual and pragmatic. Available information has not always been in form of computer data. Hence, approaches to integrate software into daily business ask for rather individual solutions and would therefore discriminate against other SMEs. This again concludes that no SME should be favored at the expense of another SME. Regardless of all difficulties, in every SME personal computers have always been available in or near production, which have been equipped with common systems. So, general computing power can be assumed as generally available for further discussions.

Further delimitations can be done regarding the purpose of the tool. Since the main objective is to facilitate improvement, the tool is not meant to be an alternative planning system. Usually enterprise resource planning-systems are used to manage and coordinate resources, information and other functions of the running business. In fact, a resource planning system can rather be seen as a useful source in order to obtain information for resource efficiency calculations. The more information a resource planning system can provide the less costly efficiency assessments will be for the SME, since information does not need to be collected for the sake of assessing resource efficiency.

In the beginning of this thesis, the basic idea has existed of creating a tool which includes a data base. That data base was supposed to store data. Nevertheless, this idea has been neg-
lected due to the insight that it has not been aiming at the right goals and also might have induced misuse. One basic thought that has led to this insight was based on the calculation approach for measures in chapter 3. In this approach, efficiency regarding different resources is calculated for different operations and for different time periods. This means, there needs to be awareness of what exactly is measured and for how long. As soon as data bases are involved there is a risk of saving a lot of different data while losing the focus. This tool ought to be supportive in identifying potentials for all kinds of manufacturing SMEs. Hence, it is regarded as reasonable and necessary that the user runs through the reflection process of what to measure, how long to measure and why whenever using this tool. In doing so, misuse can be prevented and understanding enhanced. Additionally, memory capacity of computer systems which would in this case be occupied can be used otherwise. Since it can be assumed that SMEs mostly use information out of their resource planning system for resource efficiency calculations, a further duplication of information can be avoided as well. Concluding this point, it is necessary to save results in order to compare them as time elapses, but not to an extent which makes a data base a necessity.

Generally, the idea of integrating a tool into daily business and connecting it to a resource planning system which holds its own data bases is quite interesting. On the other hand, it requires quite specialized knowledge of the organization as well as human resources in order to handle all challenges that come with an implementation. Obviously, this is rather to be done in defined project within each single SME.

With the increasing level of knowledge during this thesis work, the idea of what this tool should provide developed to a rather ‘on-demand analysis’ which enables efficiency calculation if needed, without putting the user under any constraints.

The core of the assessment calculation consists of the measures which have been developed in chapter 4. It has been concluded that customized solutions are not feasible. Collecting relevant data can therefore not be provided by a tool but has to be done manually by the user. Consequently, the start of using this tool begins with understanding of what to measure and what data to collect. It is therefore necessary to provide as much knowledge as necessary to ensure proper use. As also mentioned before, every piece of data is collected from the manufacturing line involves some kind of effort and therefore cost. The benefit resulting from the data acquisition has to be measured against this cost. In the end
the user has to decide if the benefit of particular data exceeds its cost, and therefore justifies action of collecting it.

After data has been collected, the use of the tool should then be obvious and simple. But what does that mean in detail? In terms of inserting data in the correct place, unambiguousness plays an important role. Mistakes during data input should be avoided using a convenient user interface.

When it comes to processing inserted data, single data pieces need to be related to each other properly in order to generate percentages that reflect efficiency. Preferably, this is automatically be done by the tool. Due to the fact that percentages are of major concern, adequate visualizations should be provided as well.

The evaluation method, which has been developed in the last section, is an element that has to be integrated as well in a proper way. All in all, there is a lot of information that needs to be handled. One important thing while dealing with these amounts of information is a well designed user interface which supports the user in keeping an overview. This way proper analysis can be ensured and assessments carried out more easily.

Given these insights, a supporting tool for improving resource efficiency in SMEs rather tends to have the characteristics of a decision supporting system, i.e. a computer-based system that supports decision-making activities while dealing with identifying, processing and analyzing data.

This section has addressed and discussed several difficulties that have occurred during the thesis work. Main reason for difficulties often seemed to be the fact that an applicable tool is wanted which must not be too specific in order to ensure general applicability. As discussed above, this also caused changes with regard to the thesis’ content. The following subsection discusses the choice of a platform for the software application.

### 6.2.2 Requirements and software platform

Given the discussion from the last subsection, the development of the tool is based on the following assumptions:

- Data collection is done by the user
- Interfaces to other software applications are not available
- Processing and analyzing data as main task
- Knowledge for proper use must be provided
Based on the current state of knowledge the computer program which is appointed to serve for resource efficiency calculations is *Microsoft Excel 2007*. In the following subsection the properties of this program are discussed in order to derive detailed requirements for the actual programming part.

Using Microsoft Excel 2007 (MS Excel) as a program platform is an efficient solution from many perspectives. For resource lacking SMEs this surely is the most cost-efficient solution. Not only regarding monetary values, but also in terms of acceptance by staff and learning processes. This platform can easily be used within existing computer infrastructures. It contains a lot of features and standardized applications in order to calculate and visualize percentage measures. For very special demands which exceed the regular features, individual program coding is possible based on the *Visual Basic* platform, which is also included in MS Excel. So even for special demands there is the possibility to do individual programming.

Since the application of MS Excel is widely spread among users in private and in business, implementation and learning processes can most likely be speeded up. The problem of saving relevant data is solved since savings can be done easily in the ordinary way. The data format is usually accepted and its use is convenient.

Regardless of all positive points, there are also disadvantages MS Excel is carrying along which involve risks when using it. Due to the fact that it is not a self-contained calculation module with clear user guidance, it might be misused or wrong understood if usage and purpose are not clearly defined. Risks regarding improper use must therefore be minimized. Hence, the following points must be considered:

- Clear user guidance and unambiguousness to prevent misuse
- Safety regarding information when processing and analyzing data

### 6.2.3 User interface design

So far a computer platform has been chosen to support resource efficiency improvement. The next step consists of designing the actual software. One important factor that influences the usability of a program is a carefully designed user interface. The better the user interface, the easier the desired objective can be met. This also means taking into account the user’s steps of thoughts in order to give a good and safe feeling while using the pro-
gram. Given the previous results, the tool based on MS Excel consists of four single tables. Each table is used as a screen for a particular purpose. So in total, there are four screens.

- Learning screen
- Input screen
- Evaluation screen
- Result screen

Figure 33 pictures how user and all four screens are linked to each other.

![Figure 33: Information flow between user and software](image)

**Learning screen**
The learning screen can be seen as manual for the user. It contains the knowledge which is necessary to successfully operate the program and carry out the assessment. It consists of a 6-step guideline which is discussed in the next section. Also detailed descriptions about how measures are calculated can be found in this screen. Likewise, instructions of how to handle the evaluation screen are provided. This screen consists mostly of texts and pictures and is supposed to introduce the user to the systematic approach of the tool as well as to transfer knowledge. No input is necessary from the user.

**Input screen**
The input screen deals with the data that is actually needed to calculate efficiency of various resources. This screen is the most data intensive screen since data for all measures can
be inserted. Each measure has a clearly defined area on the excel spreadsheet. In order to keep the overview, buttons from the Visual Basic toolset are used which hide calculation areas in case certain measures are not calculated. Dimensions and type of input are also defined in order to prevent misuse. Colors support the user in finding the correct cells in order to insert data. Useful information and supporting visuals which facilitate understanding of calculating measures are deposited in comment areas. This way information is easily accessible if needed. Furthermore, dynamic bar diagrams are implemented for each measure which are generated automatically as soon as the according data has been entered. The user directly benefits from entering data and feels reinforced in his action. Other elements on the screen that do not have a defined purpose are either made invisible or unable to select.

**Evaluation screen**

Though the valuation screen is not as data intensive as the input screen, the purpose and functionality must be evident to the user. In this screen the number and type of manufacturing processes need to be inserted as discussed in chapter 6.1. Like in the input screen, colored cells are used to indicate in what place data can be inserted.

**Result screen**

The result screen represents the final result of the assessment and can be used as decision support. The screen automatically gathers all resources efficiency measures from the input screen as well as the ranking from the evaluation screen and merges all results in one place. In addition, a polar diagram with one axis for each measure is generated. One important feature to mention is the flexibility of the polar diagram. Depending on what measures have been calculated, the polar diagram adjusts the number of axes accordingly to the amount of available results. Yet, the final outcome needs to be interpreted and related to its context in order to be supportive in terms of decision-making.

### 6.3 Development of a consistent assessment approach

So far a ranking method and a software program have been developed to support the assessment of resource efficiency. In this last part of the thesis, an approach is developed to ensure a uniform order of steps when using this tool. In order to ensure proper quality dur-
ing assessment of resource efficiency some sort of ‘guideline’ is indispensable. In this way, the efficiency of future assessments can be increased. At the same time comparable levels between different projects can be reached and, for instance, benchmark projects facilitated. This chapter closes with an exemplary application.

6.3.1 6 steps for assessing resource efficiency

In order to ensure a consistent procedure for all kinds of manufacturing environments, the following 6 steps are used.

![Figure 34: Consistent assessment approach](image)

**Step 1: Set system boundary**
Starting from the initial situation in SMEs, the object of investigation needs to be identified. This means to clarify what exactly has to be assessed. Relating to the unit process model in chapter 2, a system boundary needs to be set by the user. As also mentioned before, this has to be done carefully since the way in which the boundary is set directly influences time and effort of collecting necessary data. At this point the tool is not used yet. In fact, the user rather sets constraints for the following steps while defining a closed system in a manufacturing environment as depicted in Figure 35.

![Figure 35: Set the system boundary](image)
**Step 2: Insert basic information**

Once the object of investigation has been defined, it has to be detailed what is inside the system. One important thing to define is the time period of the assessment. It has to be stated for how long resources cross the defined system boundary. With regard to the tool, the user has to answer questions at the top of the input screen. Based on this information cells are marked in a different color so the user knows where to enter data in the next step. Figure 36 shows the idea of this procedure.

![Figure 36: Insert basic information into input screen](image)

**Step 3: Measure resource consumption**

In this step of the assessment approach, correct data must be identified for the previously defined object and time period. As concluded in the last section, this has to be done by the user and can be supported by the learning screen. The effort is takes to get the relevant data depends on the situation and availability at the SME.

**Step 4: Identify value-adding consumption**

Step 4 is the most knowledge-intensive step. From the total consumption of each resource, those fractions need to be identified that actually add value to the customer. Since this tool can only provide knowledge for identifying value-adding fractions of consumption, visuals of how to identify value-adding consumptions are available in the learning screen and also deposited in comment areas of the input screen for easy access. The identification of value-adding consumption leads back to the definitions of measures from chapter 4. One example of how to identify value-adding fractions of material is given in Figure 37.
Some of this information might not be available right at once. But since the main objective is to assess efficiency, it is necessary to identify the amount of resources which are actually used to fulfill customer needs. At this point a carefully chosen system boundary pays off, if it has been defined in a convenient way.

**Step 5: Insert information and rank measures**

After the consumption has been measured and the value-adding steps have been identified, the data can be inserted into the according cells of the input screen. Additionally, the type of manufacturing process as well as the type of operator should be entered in the evaluation screen. In order to do this, the user needs to assign each of the manufacturing processes, which are examined within the system boundary, to the 6 main manufacturing groups. In this way value-adding measures are ranked and copied to the result screen.

**Step 6: Interpret results**

Given that all previous steps have been conducted, the overall efficiency including a ranking of measures can be examined in the result screen. These results have to be weighed up with other information, particularly if data collection has not been accurate. Since this tool cannot fully grasp the complexity of a production system other criteria need to be taken into account when assessing resource efficiency in manufacturing. These criteria might include technology, size of machines, product specifications, batch sizes or resource prices.

### 6.3.2 Exemplary application

In this final part of the thesis the tool is used to assess the efficiency of a burning process with an ensuing assembly process. A limited set of data from industry is used for this purpose. The examined process consists of 3 steps. First the coherence of a work piece is sup-
posed to be reduced during a burning process. Afterwards, the part needs to cool down and finally be assembled manually.

**Step 1: Set system boundary**
The objects of investigation are 3 areas within a production flow. The system boundary is put around the operators, which in this case is a high temperature oven, a cooling place and an assembly area. Figure 38 shows a drawing of the defined system.

![Figure 38: System boundary of the exemplary application](image)

**Step 2: Insert basic information**
Inside the boundary the oven is the only energy consumer and machine. There is also one worker at the assembly area and one quality inspection. The cooling shelf is handled as inventory in this case. Furthermore, the covered time period is from 4 pm until 8 pm. This information is inserted on the top of the input screen as shown in Table 3.

| Number of materials? | 1 |
| Number of energy consumers? | 1 |
| Number of workers? | 1 |
| Number of machines? | 1 |
| Number of inventories? | 1 |
| Number of releases to environment? | 1 |
| Number of quality checks? | 1 |
| Number of orders? | 1 |
| Planned production time [hours] : | 4.00 |

*Table 3: Input of basic information in input screen*

**Step 3: Measure resource consumption**
Now that it has been specified what exactly should be measured and during what time period, data collection has to be done by the user.
Energy
5 parts have been operated in one batch during the time period of 4 hours. In order to identify the total energy consumption, invoices and reports are feasible. Those can be requested of the energy supplier. Figure 39 shows load curves of the building the oven is positioned in. These load curves have been measured on an hourly basis during a closed observation interval of 22 days. Each load curve describes the course of total consumption during one day. The variations of the load curves result from differently timed manufacturing activities.

![Figure 39: Daily load curves of a building (22 days)](image)

Workers
The planned production time within the time period is 4 hours at the assembly area, which can be regarded as half of one working day.

Machining
The planned production time of the oven is 4 hours and equals the defined time period for this examination.

Inventory
The size of the cooling shelf in which parts cool down has been measured. The room of the shelf is approximately 4 m³. There is no data available to calculate to turnover of inventory.
Quality
The quality check is done after the products have been assembled. During the defined time period 8 parts have been checked.

Step 4: Identify value-adding consumption
At this point further investigations have to be made in order to identify the value-adding fractions.

Energy
The easiest way to identify value-adding consumption is to measure consumption directly with a mobile instrument. Alternatively the total consumption of a building can be broken down further according to the hierarchical system of a plant [3]. Since there are no instruments available, the increase or decrease of the total consumption must directly be allocated to start-up or switch-off of machines. So the type of investigations that have to be made is to find out when the oven was switched on or switched off. Subsequently, standby consumption and value-adding consumption can be estimated using load curves as depicted in Figure 40.

![Load curves several days](image1)
![Load curve single day](image2)

**Figure 40: Identification of fractions of consumption using load curves**

As introduced in chapter 4, energy consumption of a manufacturing plant can be broken down in 3 components: The standby consumption of the plant, the standby consumption of the operating unit and the consumption during machining cycles. Given the load curves of the left graph in Figure 40, the standby consumption of the building can be assumed to be roughly 55 kW as indicated by the dotted line.
After having discussed the circumstances with operators on-site, the oven was switched off at 8pm. As shown in Figure 40, the right graph describes the total consumption of that single day as well as when the oven has been switched off. From the moment of switch-off, the oven has been running in standby mode until next shift while the remaining production in this building kept running. As a consequence the total consumption of the building decreased 61 kW which can be regarded as the amount of energy that is necessary to add value to the customer in this process. Since the oven usually remains in standby mode after switch-off, the standby consumption of the oven is included in the standby consumption of the building.

Additionally it should be noted, that measures regarding load curves in this case are done on an hourly base. This means load curves consist of single measurement points which are connected with a line. Hence, the slope between 8 pm and 9 pm during the switch-off of the oven can be neglected.

**Workers**

The worker needs a time period of 20 minutes per part in order to finish the assembly task. A number of 8 parts have been finished during the defined time period. So the total value-adding time has been 160 minutes.

**Machining**

The oven runs continuously during the time period of 4 hours. Since there are no breakdowns, the planned production time has been used to its full extent.

**Inventory**

The volume of the product can be estimated with approximately 0.04 m\(^3\). During the defined time period 20 parts have been placed in the cooling shelf. So the occupied space has been 0.8 m\(^3\).

**Quality**

All parts have passed quality control successfully.
Step 5: Insert information and rank measures

The collected information has to be inserted in the input screen and the evaluation screen. In order to rank value-adding measures, 2 processes have to be assigned to the according group of manufacturing processes. Since the burning process is aiming at reducing the coherence of work pieces it belongs to the group of mass-change processes. The assembly is a consolidation processes which is carried out manually.

Step 6: Interpret results

After data has been inserted, the final result can be observed in the result screen as depicted in Figure 42. The table on the left hand side shows all measures and their efficiency as far as data has been inserted in the input screen and the evaluation screen. Additionally, a polar diagram has been generated using only the measures which have been calculated.

![Overall efficiency](image)

<table>
<thead>
<tr>
<th>Overall efficiency</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material efficiency</td>
<td>1</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>53%</td>
</tr>
<tr>
<td>Availability</td>
<td>100%</td>
</tr>
<tr>
<td>Machining speed</td>
<td></td>
</tr>
<tr>
<td>Worker efficiency</td>
<td>67%</td>
</tr>
<tr>
<td>Quality</td>
<td>100%</td>
</tr>
<tr>
<td>Delivery speed</td>
<td></td>
</tr>
<tr>
<td>Dependability</td>
<td></td>
</tr>
<tr>
<td>Health rate</td>
<td>100%</td>
</tr>
<tr>
<td>Used space</td>
<td>20%</td>
</tr>
<tr>
<td>Number of inventories</td>
<td>1</td>
</tr>
<tr>
<td>Number of environmental releases</td>
<td></td>
</tr>
</tbody>
</table>

Figure 41: Result of the exemplary application

Availability, health and quality have been rated at 100%. Since the defined time period of 4 hours exactly covered one machining cycle of the oven, an availability of 100% is evident. As all of the assembled parts have been free of error and likewise there has not been sick-leave, the results of quality and health rate are reasonable.
Energy efficiency is has been rated with 53%. Remembering that the oven has had a value-adding consumption of 61 kW and the standby consumption of the building and the oven has all together been 55 kW, an efficiency of 53% per machining cycle seems to be a realistic result. In order to increase energy efficiency either the total consumption can be reduced while keeping the output of the oven at a constant level, or the value-adding shares of the total consumption can be increased. It is also feasible to investigate the size of energy loss during value-adding processes of the oven.

Looking at worker efficiency, approximately one third of the planned production time is not used for value-adding activities. At this point further examinations towards reduction of set-up times, waiting times or searching times can be done.

The shelf for letting parts cool down has been examined as an inventory. A rate of used room has been quantified with 20%. This could be a temporary result since only 4 hours have been examined. Otherwise a reduction of shelf can be considered as useful in order to save space.

Taking into account the ranking of value-adding measures, material efficiency has been ranked the most relevant one. On the other hand energy efficiency has been ranked as least relevant. One might wonder how this result has come up since material has not been measured in this example. As the ranking is only based on types of manufacturing processes, in which the burning process is considered as mass-change process, material efficiency has been weighted higher than in energy efficiency. Furthermore, machining activities and manual activities are both ranked equally as second. Since there is an equal number of machining and manual activities within the system boundary and both measures are weighted equally for each manufacturing process, they consequently have the same rank. So in this example the weights used in the ranking method do not properly reflect the relevance of measures.

From this point on forward additional information is needed to find out which of these revealed potentials is the most worthwhile to realize. Furthermore, additional data would be useful in order to calculated delivery speed and dependability. Both measures could help to get a better picture about the entire production flow and the organization between oven, cooling shelf and assembly.
7 Discussion of results

This chapter begins with a summary of the most important results from the thesis. This is followed by a general discussion.

The objective of this thesis has been the development of a tool to facilitate the increase of resource efficiency in small and medium-sized enterprises. In order to meet this objective, two research questions have been proposed.

Research question 1: What are appropriate measures for quantifying resource efficiency?

Research question 2: How can applicability of a computer-based tool be ensured for various SMEs in different manufacturing industries?

Based on the first research question, resource efficiency measures have been designed for different types of resources in order to get a balanced set of measures. To stimulate improvement, the total consumption of resources has been related to its value-adding fraction of consumption. The result has shown that direct saving potentials can be identified and that further information about the single organization and its strategy is needed to enable more detailed analyses about the relevance of resources.

Based on the second research question, a case study has been carried out to learn more about applicability in SMEs. The outcome has revealed that software, which is implemented in SMEs, has to meet lowest common requirements and consider the fact that there is no initial data level. This case study has further revealed that a lack of knowledge might be the reason for a different perception of what resource efficiency actually means. Likewise, it can be assumed that this lack of knowledge is also the reason for not realizing great saving potentials.

Based on these results, a computer-based tool has been developed which is based upon three fundamental pillars.

The first pillar consists of a ranking method for value-adding resources. Using manufacturing processes as criteria, this method ranks measures for value-adding resources according to their relevance. This method is based on the concept of value benefit analyses which enable the ranking to be comprehensible as well as systematic while covering all manufac-
turing processes. Since the influence of manufacturing process on resources is based on subjective weighting, the result has to be reflected carefully in order to provide support in decision-making with regard to improvement activities.

Secondly, a software platform has been chosen and a program designed. The developed program has the characteristics of a decision-support system and consists of 4 separate screens in a Microsoft Excel file. Each screen fulfills a certain purpose and supports the user in carrying out resource efficiency assessment.

The third pillar gives attention to providing a consistent way of accomplishing the process of resource efficiency assessment. A series of 6 steps has been developed in order to guide the user from the initial situation in the SME to the assessment of its resource efficiency. With this consistent approach the efficiency of future assessments can be increased and benchmarks facilitated.

On the one hand, the tool offers a lot of features. It bundles know-how, supports data handling and visualizations as well as decision-making in a step-by-step approach. The consistent approach highlights important steps which need to be taken in order to carry out assessments from any initial situation in any SME. The tool tries to be specific without narrowing down the group of potential users. It enables assessments independently from industry and specific environment of the single organization. Furthermore, it helps to enhance the understanding of efficient manufacturing and assists in getting away from purely cost-oriented perspectives while rather focusing on cost-driving factors.

On the other hand, there are points that have been left unconsidered. In software design the problem of data collection, the integration of the program into existing computer environment and the individual level of knowledge have been left out of scope. Criticism can also be raised to the approach of quantifying resource efficiency. The measures which have been designed for quantifying resource efficiency only focus on direct savings. Little work has been completed on the problem of analyzing indirect resource savings resulting from complexity in production systems. Hence, the tool focuses on a quite ‘shortsighted’ approach. Additionally, the user must come up with own practical ideas about making improvements after potentials have been identified. One main reason though for not having covered these points has been the nature of the main objective, i.e. to provide a generally applicable tool for a variety of very different and specialized enterprises. So, as already indicated previously, general applicability is only achievable at the expense of individual
solutions. Specific issues like data collection or analysis of indirect resource savings require detailed on-site information which is opposing to the idea of providing a consistent approach.
8 Conclusion and future work

One important question to answer at this point is whether the main objective has been met or not. The main objective has been formulated in chapter 1 as:

*Development of a tool which facilitates the increase of resource efficiency for small and medium-sized enterprises*

Surely, a lot of work has been done regarding resource efficiency in SMEs. But it still is arguable if the result can be considered as ‘facilitation’ for SMEs to increase their resource efficiency. As mentioned in the beginning of the thesis, SMEs are usually not able to deal with organizational issues besides their daily business. As a result, this tool offers the opportunity to access and to go about the problem of resource efficiency in a comprehensible and less costly way. Of course, acceptance within a company cannot be guaranteed. Depending on the focus of the management, this tool will be regarded as worthwhile or not. So, if data is collected and inserted properly, the tool can tap its full potential by revealing improvement opportunities and providing decision support. When looking at the initial situation in most SMEs, this tool definitely supports reducing the lack of methodology in a quite pragmatic way. Taking into account all previously mentioned arguments, it can be stated that the objective to develop a tool which facilitates the increase of resource efficiency in SMEs has been met.

However, there still is need for future work. One next step to take is the integration of the tool into the SMEs’ environment. A higher degree of facilitation can be reached by a more customized use. In order to further enhance resource efficiency in SMEs, more details regarding indirect savings resulting from interrelations in production systems are necessary. An important task at this point is to investigate how hidden potentials can be identified systematically so improvement projects can be initiated and carried out successfully.
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