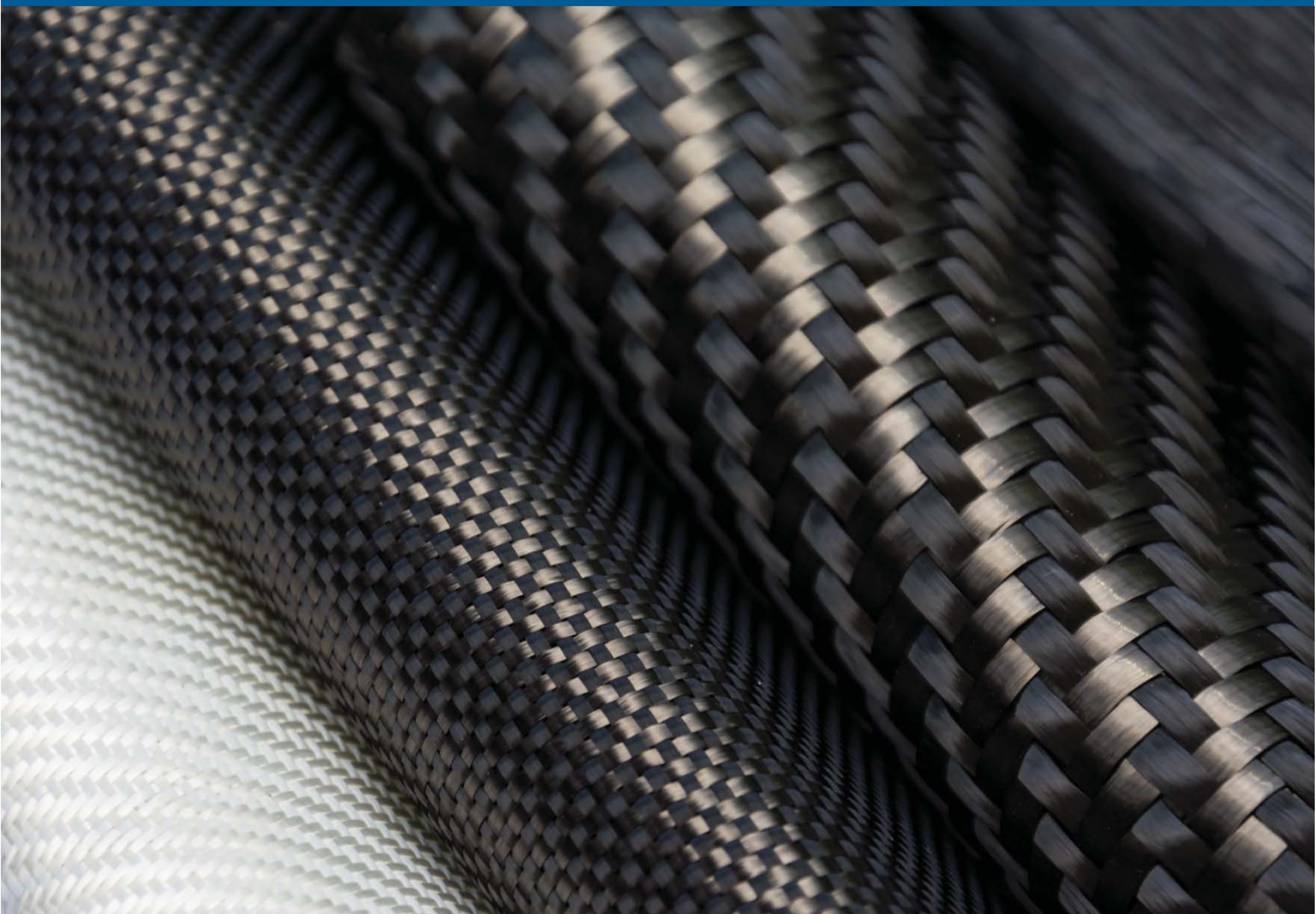
STUTTGARTER BEITRÄGE ZUR PRODUKTIONSFORSCHUNG

ERIN SHEEHAN

# A Simulation-Based Method for Improving Material Efficiency within the Constraints of Existing Production Systems



Universität Stuttgart

Fraunhofer IPA

STUTTGARTER BEITRÄGE ZUR PRODUKTIONSFORSCHUNG BAND 78

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# GELEITWORT DER HERAUSGEBER

Produktionswissenschaftliche Forschungsfragen entstehen in der Regel im Anwendungszusammenhang, die Produktionsforschung ist also weitgehend erfahrungsbasiert. Der wissenschaftliche Anspruch der „Stuttgarter Beiträge zur Produktionsforschung" liegt unter anderem darin, Dissertation für Dissertation ein übergreifendes ganzheitliches Theoriegebäude der Produktion zu erstellen.

Die Herausgeber dieser Dissertations-Reihe leiten gemeinsam das Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA und jeweils ein Institut der Fakultät für Konstruktions-, Produktions- und Fahrzeugtechnik an der Universität Stuttgart.

Die von ihnen betreuten Dissertationen sind der marktorientierten Nachhaltigkeit verpflichtet, ihr Ansatz ist systemisch und interdisziplinär. Die Autoren bearbeiten anspruchsvolle Forschungsfragen im Spannungsfeld zwischen theoretischen Grundlagen und industrieller Anwendung.

Die „Stuttgarter Beiträge zur Produktionsforschung" ersetzt die Reihen „IPA-IAO Forschung und Praxis" (Hrsg. H.J. Warnecke / H.-J. Bullinger / E. Westkämper / D. Spath) bzw. ISW Forschung und Praxis (Hrsg. G. Stute / G. Pritschow / A. Verl). In den vergangenen Jahrzehnten sind darin über 800 Dissertationen erschienen.

Der Strukturwandel in den Industrien unseres Landes muss auch in der Forschung in einen globalen Zusammenhang gestellt werden. Der reine Fokus auf Erkenntnisgewinn ist zu eindimensional. Die „Stuttgarter Beiträge zur Produktionsforschung" zielen also darauf ab, mittelfristig Lösungen für den Markt anzubieten. Daher konzentrieren sich die Stuttgarter produktionstechnischen Institute auf das Thema ganzheitliche Produktion in den Kernindustrien Deutschlands. Die leitende Forschungsfrage der Arbeiten ist: Wie können wir nachhaltig mit einem hohen Wertschöpfungsanteil in Deutschland für einen globalen Markt produzieren?

Wir wünschen den Autoren, dass ihre „Stuttgarter Beiträge zur Produktionsforschung" in der breiten Fachwelt als substanziell wahrgenommen werden und so die Produktionsforschung weltweit voranbringen.

Alexander Verl    Thomas Bauernhansl    Engelbert Westkämper

# A Simulation-Based Method for Improving Material Efficiency within the Constraints of Existing Production Systems

Der Fakultät Energie-, Verfahrens- und Biotechnik
der Universität Stuttgart
zur Erlangung der Würde eines Doktor- Ingenieurs (Dr.-Ing.)
genehmigte Abhandlung

von

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2018

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Den größten Dank schulde ich meinem lieben Mann Klaus. Er hat mir stets zur Seite gestanden, immer Verständnis gehabt, mich liebevoll unterstützt und stets motiviert, meine Dissertation zu vollenden. Deshalb widme ich ihm diese Arbeit.

## Kurzfassung

Mit steigenden Material- und Lohnkosten, erstrebt die produzierende Industrie eine Steigerung der Materialausbeute ohne die Beeinträchtigung logistischer Ziele in bestehenden Produktionssystemen. Aufgrund des unvollständigen Verständnisses der vielfältigen Ursachen der Materialabfälle bleiben jedoch lokale und isolierte Optimierungen die Regel.

Um Produktionszuständige zu befähigen geeignete Instrumente für ganzheitliche Materialeffizienz zu selektieren, präsentiert diese Arbeit eine simulationsbasierte Lösung zur parallelen Modellierung der Abfallkausalität und der Leistung eines Produktionssystems.

Eine Ishikawa-Analyse zwölf üblicher Abfallarten adressiert den Bedarf für ein tiefgreifendes Verständnis der Materialflüsse und ihrer Ursachen. Die Konsolidierung und Zusammenfassung der Ursachen ergibt vier Mechanismen zur Beeinflussung der Menge und Wert der Materialabfälle in bestehenden Produktionssystemen: Steigerung der Häufigkeit oder der Dauer materialverbrauchender Aktivitäten, Steigerung der Abfallmenge je Aktivität und die unnötige Verkopplung von Abfällen mit Aktivitäten.

Mit dieser Kenntnis adaptiert der Autor die bestehenden Modellstrukturen, z.B. die Betriebszustandsmodellierung zur Entstehung der Materialabfälle in der Fabrik. Anhand des Materialeffizienzmodells der Fabrik lassen sich die Stellhebel zur Steigerung der Materialeffizienz auf Fabrikebene darstellen.

Die entwickelte Methode beginnt mit einer Ist-Aufnahme, um den Zusammenhang zwischen Materialabfällen und relevanter Aktivitäten festzustellen. Verbesserungsszenarien lassen sich in einem zweiten Schritt anhand einer systematischen Vorgehensweise ableiten. Eine System Dynamics basierte dynamische Produktionssimulation untersucht die Effektivität der Verbesserungsmaßnahmen.

## Short Summary

With increasing material and labor costs, manufacturers seek to increase material yield in existing production systems without sacrificing logistical performance. However due to a lack of understanding of the material waste causality and its interdependencies, localized and isolated material efficiency efforts are commonplace.

To enable manufacturers to select the best-suited instruments for holistic material efficiency, this thesis presents a simulation-based method, modelling the causality of material waste parallel to manufacturing performance.

An Ishikawa analysis of twelve material waste forms addresses the need for deeper understanding of material waste causation. Through abstraction, four types of causes are identified: those setting the frequency and duration of waste-linked activities, those determining the amount of waste per activity, or unnecessarily linking waste to an activity. Based on this finding, the author adapts existing resource consumption modelling structures, e.g. machine operating states, to industrial waste. A model of the factory is developed to illustrate the mechanisms for controlling material waste.

The developed procedure begins with a current state survey to examine the relation between material waste and activities of the factory. A systematic method allows the user to generate a list of improvement scenarios. The effectiveness of the improvement measures is investigated in dynamic production simulation (system dynamics).

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## List of Acronyms

| | |
|---|---|
| ANN | Artificial Neural Network |
| CFD | Computational Fluid Dynamics |
| CLOM | Closed-Loop Operating Materials |
| $CO_2$ | Carbon Dioxide |
| DES | Discrete Event Simulation |
| DIN | German Institute for Standardization |
| FEM | Finite Element Method |
| FIFO | First-In-First-Out |
| FMEA | Failure Modes and Effects Analysis |
| I-O Analysis | Input-Output Analysis |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Analysis |
| LIFO | Last-In-First-Out |
| MCE | Material Cost Efficiency |
| ME | Material Efficiency |
| MFA | Material Flow Analysis |
| MFCA | Material Flow Cost Analysis |
| MTTF | Mean Time to Failure |
| MTTR | Mean Time to Repair |
| NPO | Non-Product Output |
| OEE | Overall Equipment Effectiveness |
| OM | Operations Management |
| PPC | Production Planning and Control |
| R&D | Research and Development |
| REFA | German system for checking working hours |
| SD | System Dynamics |
| SMED | Single Minute Exchange of Dies |

| | |
|---|---|
| USD | United States Dollar |
| VSM | Value Stream Mapping |
| WQ | Waste Quantity |
| WR | Waste Rate |
| WIP | Work in Process |

# 1 Introduction

## 1.1 Current Situation

Increased economic development and wealth worldwide has created a culture of manufacturing, consumption, and disposal. Between 2005 and 2015, global economic activity in manufactured goods increased by 50%, paired with a 25% increase in global gross domestic product (The World Bank 2016; WTO 2016, pp. 30). While industrialization increases quality of life, it is accompanied by an increase in virgin material extraction, shorter product lifecycles, and increased volumes of industrial and post-consumer waste, which result in concerns over resource scarcity, emissions generation, and social and political instability.

Large shares of extracted virgin materials are discarded as industrial waste, including both materials lost in the manufacturing process and operating materials consumed in the manufacturing process. In the United States, 93% of natural capital extracted for production purposes is lost before sale as a final product (Abdul Rashid 2009, pp. 9). Case studies from Milford et al. have shown that accumulated yield losses over the process chain for sheet metal products are as high as 50%, with similar figures for the packaging and printing industries (Milford et al. 2011, pp. 1194; Allwood 2013, pp. 4).

The increasing scarcity of virgin materials and increasing demand through industrialization may lead to increasing commodity price volatility in the coming years (Biebeler 2014b, pp. 10). Adjusted to USD in 2016, Figure 1 demonstrates the volatility of commodity prices in the last 25 years based on the International Monetary Fund's (IMF) non-fuel commodity price index, adjusted for inflation with a consumer price index. For companies processing raw commodities, sudden price fluctuations can easily wipe out profit margins.


**Figure 1: IMP Non-fuel commodity price index. Data source: (IMF 2016; US BLS 2016)**

In addition to price volatility, high material prices are identified as the most significant motivator for manufacturers to pursue material efficiency in a survey of the German industry (Biebeler 2014b, pp. 12). Cutting material costs presents a powerful leverage factor in maintaining manufacturing profitability in mature or maturing markets. On average, material costs comprise approximately 40% of production costs for the German industry, while labor costs comprise only 25%, and energy costs, a mere 2% (Baron et al. 2005, pp. 1; Blaeser-Benfer 2012, pp. 4).

With most companies focusing on labor costs and more recently energy cost reduction, material costs are often deemed a “blind spot” for companies (Kristof et al. 2010, pp. 9). The increasing material cost share of manufacturing costs for German manufacturers (see Figure 2) supports this statement. Similarly, the body of research on labor productivity greatly exceeds that of material productivity, which may be a remnant of a time with expensive labor and abundant resources (Abdul Rashid 2009, pp. 8).

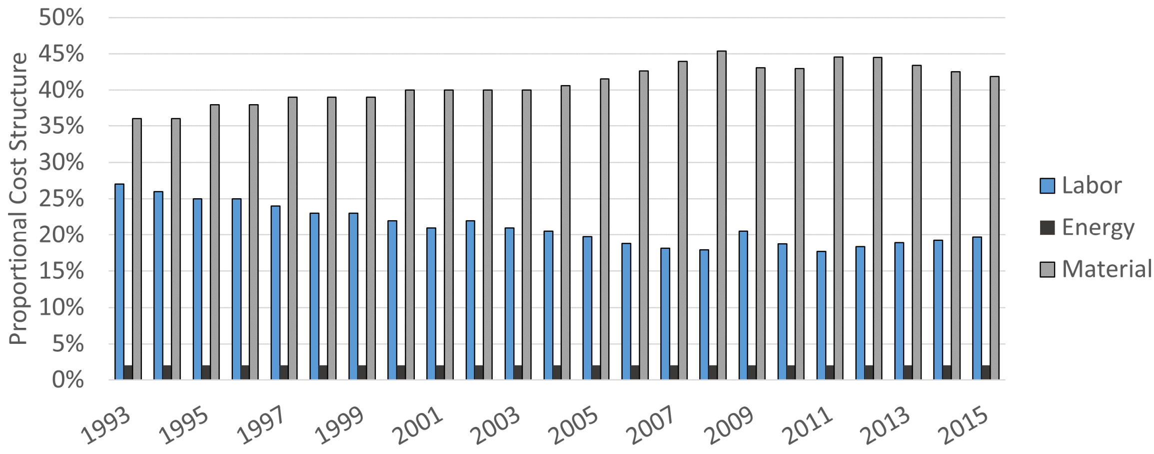



**Figure 2: Average German manufacturing cost structure (Destatis 2017)**

A recent survey revealed that approximately 7% of material costs in manufacturing are attributed purely to material waste, corresponding in 48 billion Euros annually in Germany. Companies that produced complex products, e.g. electronics, reported a higher than average potential for material cost savings, as shown in the branch break-down in Figure 3 (Fraunhofer ISI 2011, pp. 2).

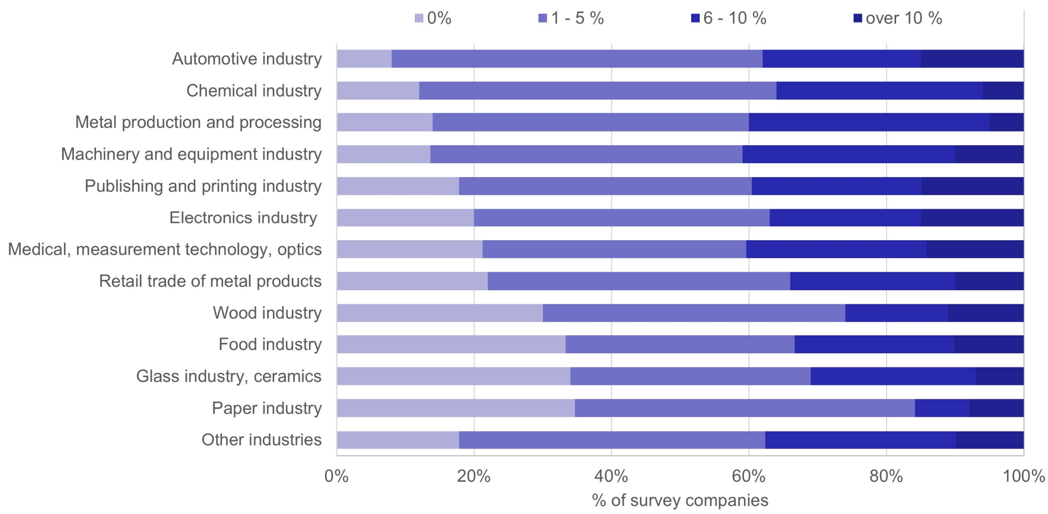



**Figure 3: Potential for material cost savings (Fraunhofer ISI 2011, pp. 8)**

More recently, sustainability initiatives have shed light on the topic of material efficient product designs, manufacturing processes, and business models. Experts estimate the purchase cost of wasted materials amounts of 40-70% of the total environmental costs for manufacturers (Jasch 2009, pp. 80). Yet few bodies of work investigate the multiple causes of material waste a manufacturing system, considering the interworking of multiple machines, employees, and material flows, to better understand the effects of decision-making on material costs in the factory. This problem is described in detail in the following section.

## 1.2 Problem Description

With increasing material and labor costs, manufacturers are seeking to increase material yield in production systems while maintaining productivity and agility. Although the real material yield of a production system is partially predefined by product design and production system design, it is also influenced by operations on the shop floor, including production scheduling, maintenance activities, and employee qualification (Inman et al. 2003, pp. 1954; Li et al. 2008, pp. 162).

Increasing material yield requires consideration of multiple material flows, which each serve a unique purpose in the factory. Losses in material quality and material value occur for diverse reasons, including damage, deterioration, decay, and contamination and may be linked to number of planned activities and unplanned factory events. Without sufficient knowledge of the causal relationships leading to the occurrence of material waste and resulting from its occurrence, minimizing material waste, or maximizing material yield is impossible.

Missing information on prioritization of material efficiency improvement activities in a company is cited as an obstacle for manufacturers in increasing material efficiency (Abdul Rashid 2009, pp. 218). Additionally, manufacturers face the following hurdles when making material efficiency decisions at the aggregate level:

- History of local optimization: scholars and practitioners have optimized material flows individually and locally, in a single manufacturing process.
- Unknown interdependencies: system adjustments to eliminate one waste form may increase the occurrence of others material waste forms. For instance, a lot size increase may reduce startup losses and setup consumables, while increasing process defects later in the run and inventory deterioration.
- Unclear responsibilities: manifold company functions influence material efficiency, including purchasing, quality management, production, product design, facility management and environmental management (Kaltschew et al. 2012, pp. 251).
- No common denominator: Apart from monetary cost and mass, no common denominator for measuring material efficiency is available (Biebeler 2014b, pp. 25).

Scholars have attempted to predict the material efficiency of a manufacturing system following fuzzy logic, artificial neural network (ANN) and simulation-based methodologies, allowing manufacturers to explore the effect of material efficiency activities on their material cost and performance (Huang et al. 1993; Luo et al. 1997; Alvandi et al. 2015). However, these approaches consider only a limited number of material flows and production stages, and require a rigorous, case-specific understanding of material waste causality. For manufacturers to improve their policies, a structured method for investigating material waste causality and manufacturing performance is necessary.

## 1.3 Focus and Boundaries

This work presents a structured method to model factory systems and identify the appropriate course of action to increase material efficiency through operative decision-making. Factory material efficiency is considered the minimization of destruction, deterioration, and irretrievable loss of all engineered materials in the factory. This is represented in Figure 4 by the thick black arrow.

The mission of this thesis is to support manufacturers in selecting the correct instruments to prevent material waste flows without sacrificing factory performance, rather than developing material efficiency instruments (e.g. nesting algorithms). Consequently this is considered a factory-level approach, represented by the grey factory in Figure 4.

The scope encompasses only instruments and approaches within the authority of operations management, which can be executed without changes to the product design or process specifications. Examples include job scheduling approaches (e.g. lot-sizing and sequencing), inventory management, maintenance planning, and employee qualification.

Figure 4 demonstrates this aspect by highlighting the operative decision-making level.

The method serves to support operative decision-makers in preventing loss and destruction of material in the factory setting. For that reason, internal material repair processes and internal recycling processes are not considered. This is represented by the focus on waste prevention in Figure 4.

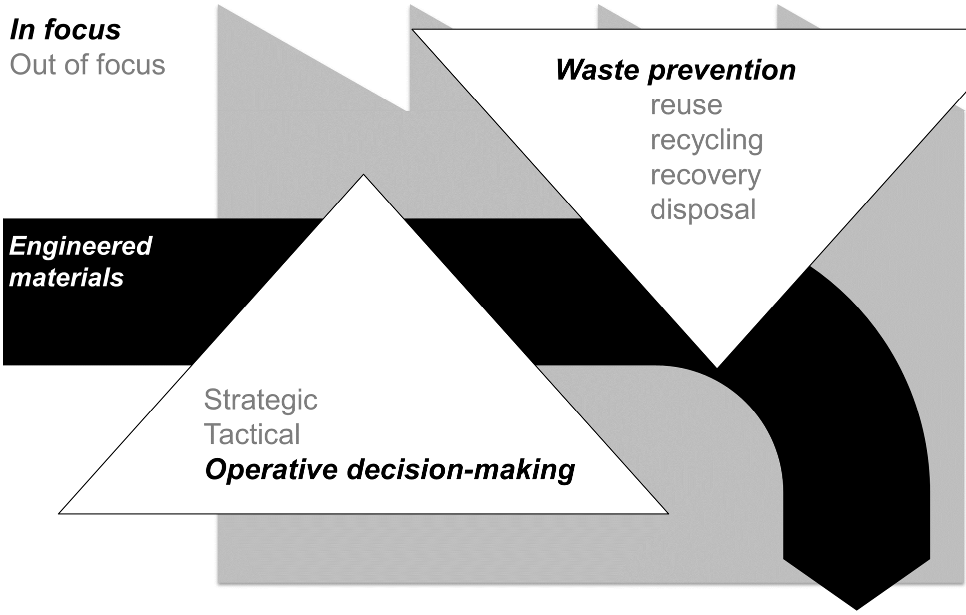



**Figure 4: Focus on waste prevention through operative decision-making**

## 1.4 Research Question

With the motivation and boundaries set respectively in 1.2 and 1.3, a single research question is formulated to concisely describe the objective of this work:

*How can material efficiency be increased through operative decision-making within the constraints of existing manufacturing systems, without impeding other logistical and cost goals?*

To thoroughly address the overarching research question, the author derives a set of sub-questions, as shown in Table 1. The first six sub-questions dissect and specify the text components of the overarching question, such as 'manufacturing systems', 'operative decision-making', 'goals', and 'material efficiency', in line with the focus established in 1.3.

The second set of questions address the 'how' in the research question. This includes selecting the best-suited methodological approach (dynamic production simulation), addressing the deficits of the existing solutions in this field and formulating solution specifications.

| Sub-question | Linked text in research question | Addressed in section: |
|---|---|---|
| Understanding the components of the question: | | |
| What are the limits and constraints of a manufacturing system? | within the constraints of existing manufacturing systems | 2.1 |
| What are the limits of the authority of operative decision makers? | through operative decision-making | 2.1 |
| What are the goals of manufacturing systems? | without impeding other logistical and cost goals | 2.1 |
| Which materials are used or processed in a manufacturing system? | material efficiency … within … existing manufacturing systems | 2.2 |
| How does a material use its utility in a factory setting? | material efficiency … within … existing manufacturing systems | 2.2 |
| What is material efficiency within the context of a manufacturing system? | material efficiency … within … existing manufacturing systems | 2.3 |
| Requirements on the solution: | | |
| Which methodological approach is best suited for addressing this problem? | How... | 3 |
| What are the deficits of the current solutions? | How... | 4.1, 4.2 |
| What specifications are required to better address the problem? | How... | 4.3 |
| Design of the solution: | | |
| How can the causality of material efficiency be modelled? | How... | 5 |
| How can material efficiency of the factory model be increased? | How... | 6 |
| How can practitioners increase material efficiency in their factories? | How... | 7 |

**Table 1: Sub-questions derived from the research question**

The third and final set of questions accompanies the fulfillment of the solution specifications. Since a simulation-based method is developed, the questions address the functionalities and design of the model. The last question addresses the practical procedure for increasing material efficiency within manufacturing systems considering the abovementioned constraints.

## 1.5 Scientific Positioning and Reference Framework

In this following section positions the developed method within the applied sciences and establishes the scientific assumptions, which form the basis for this work. Based on the established premises, the author develops a fitting research process for this explorative journey in Section 1.5.2. Throughout the iterative process, the author seeks to refine the reference framework of this thesis. The starting point for this iterative process is established in Section 1.5.3.

### 1.5.1 Scientific Positioning

Science encompasses both the formal sciences, which are concerned with the study of formal systems, and the physical sciences, concerned with the study of real systems. Formal sciences attempt to characterize abstract structures through constructing sign systems, including logic, mathematics, statistics, and philosophy. The formal sciences, unlike physical sciences, bear no relation to reality, only their logical truth can be proven (Ulrich et al. 1976, pp. 305).

In contrast physical sciences strive to describe, explain, and control phenomenon as an empirically observable section of reality, as shown in Figure 5 (Ulrich et al. 1976, pp. 305). Due to their strong relevance to reality, the physical sciences are subject to an additional criteria in their testing: factual truth (Ulrich et al. 1976, pp. 306).

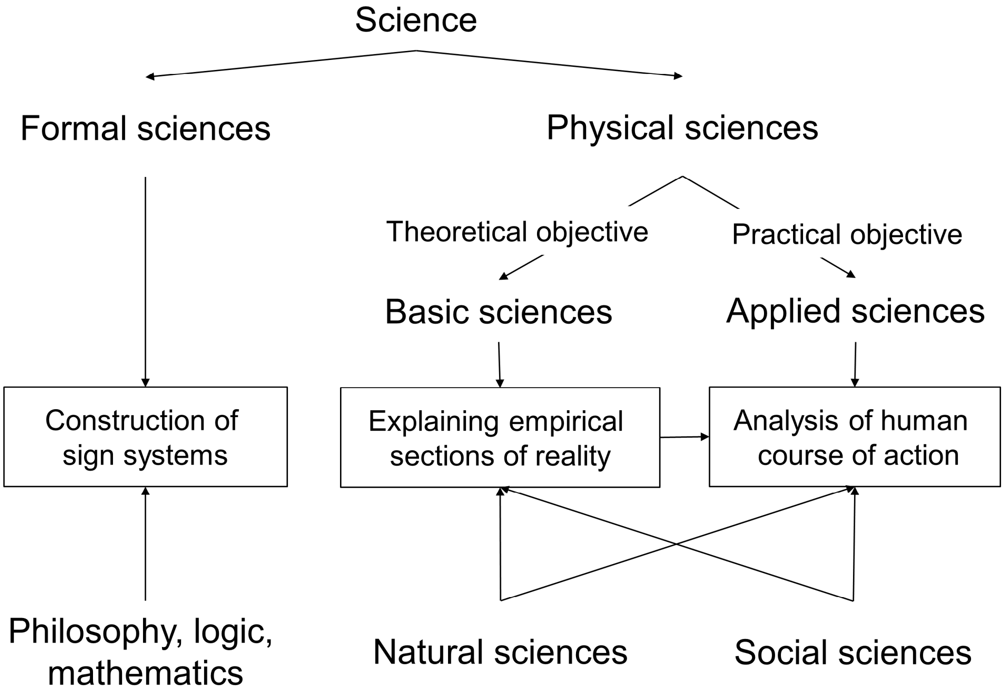



**Figure 5: Systematic of the sciences (Ulrich et al. 1976, pp. 305)**

Physical sciences can be further divided into basic sciences and applied sciences. Basic sciences seek to explain phenomena and therefore the formation of explanatory models takes the foreground. In contrast applied sciences aspire to analyze alternative courses of action for the design of social and technical systems, yielding decision models and decision processes (Ulrich et al. 1976, pp. 305).

Ulrich identifies the following distinguishing elements of the applied sciences from basic research, as shown in Table 2. While in the basic sciences, the researched problems stem from e.g. discrepancies in theory, the researched problems of the applied sciences stem from practical application. Scientists of the basic sciences define research problems with the objective of explaining phenomenon in an existing reality, making the current reality the subject of their studies, while scientists of the applied sciences seek rules and models to create new realities, using the current reality merely as a starting point to explore new realities. The basic sciences test their hypotheses using empirical methods, while in the applied sciences these serve to generate the relevant problems of the practice and test the developed design models. Therefore Ulrich deems the practice as constitutive to the applied sciences, while it is merely accessorial for the basic sciences (Ulrich 1981, pp. 10).

**Table 2: Traits of the applied sciences (Ulrich 1981, pp. 10)**

| | *Basic sciences* | *Applied sciences* |
|---|---|---|
| *Origin of problem descriptions* | Theory | Practice |
| *Objective* | Explanation of phenomena in the existing reality | Rules and models for the creation of new realities |
| *Relation to current reality* | Subject of investigation | Starting point for investigating other realities |
| *Significance of empiricism* | Means of testing hypotheses | Means of surveying problems and testing design models |
| *Relation to practice* | Accessorial | Constitutive |

This thesis interprets manufacturing organizations as part of the complex, open, social system following the principle of Punch and Saunders et al., which are subject to a multitude of transformations (Punch 2005, pp. 25; Saunders et al. 2009, pp. 136). Organizations cannot be assumed completely controllable based on the considerations of Ulrich & Krieg (Ulrich et al. 1974, pp. 13). Therefore, the field of business management, which strives to investigate effects of human courses of action, is understood as an applied science. The engineering sciences are also considered applied sciences. This thesis bridges both business management and the engineering sciences to investigate the ability to reduce material waste within operations management (OM). The problem formulation is identified in the industrial practice.

### 1.5.2 Research Process

Ulrich states that knowledge generation is inductive in applied research, while deductive in basic research (Ulrich 1995, pp. 165). The minimization of aggregate material consumption of manufacturing systems stakes out a complex and up until now inadequately addressed problem formulation derived from the practice, for which there is no suitable approach. For that reason a purely inductive approach based on empirical observations would be insufficient for knowledge generation. On the other hand, there is no theoretical foundation for minimizing aggregate material waste, rendering a purely deductive approach also inadequate.

Therefore an inductive-deductive approach is combined with a model-oriented simulation approach to support the validation of the developed method and support the discovery of interdependencies and principles.

In accordance with Kubicek and Tomczak, an iterative inductive-deductive research process is derived, with the goal of refining the reference framework of this thesis, or more specifically an understanding of the interworking of aggregate material efficiency and other factory cost and market goals. The first loop of the research process starts with the build-up of knowledge through secondary research, then deriving questions on the formed reality. To investigate the defined questions, data from expert interviews, case studies, and direct experience is collected and interpreted. In turn, through induction a stronger and more comprehensive theory is formed with every loop. In later loops, data is also generated through experiments in simulation models. At the point of publication of this work, the iterative process is frozen.

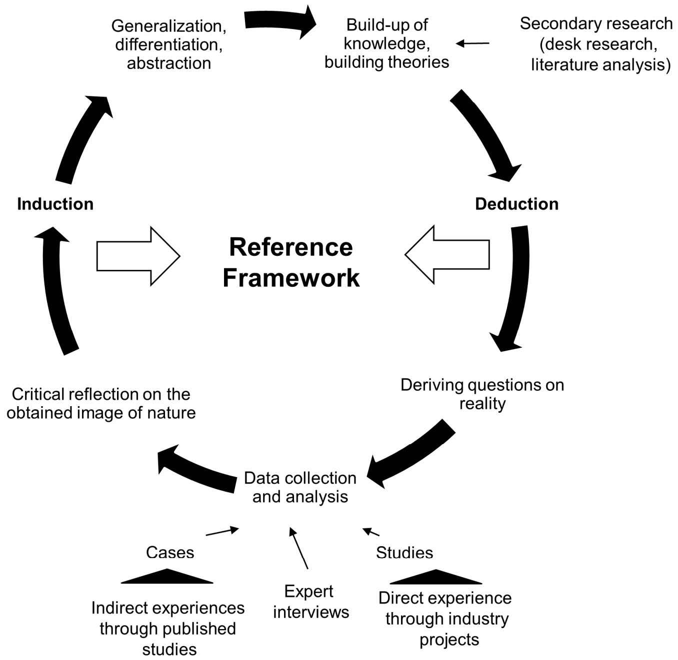



**Figure 6: Research process, in accordance with (Kubicek 1976; Tomczak 1992)**

### 1.5.3 Reference Framework

As described in the last section, a rough reference framework serves as the starting point for the iterative research process. This work investigates the interaction between operative decision-making and the occurrence of material waste forms, forming the first two elements of the reference framework of this thesis (see Figure 7). After gaining knowledge on the interdependencies of material waste forms and operative decision-making, the author constructs a model to demonstrate the mechanisms within the authority of operative decision-making to reduce aggregate material waste, represented in Figure 7 as material efficiency. The subsequently developed simulation-based method provides a structured procedure for selectively investigating effects of modified operative decision-making on aggregate material waste and the fulfilment of market and cost goals.

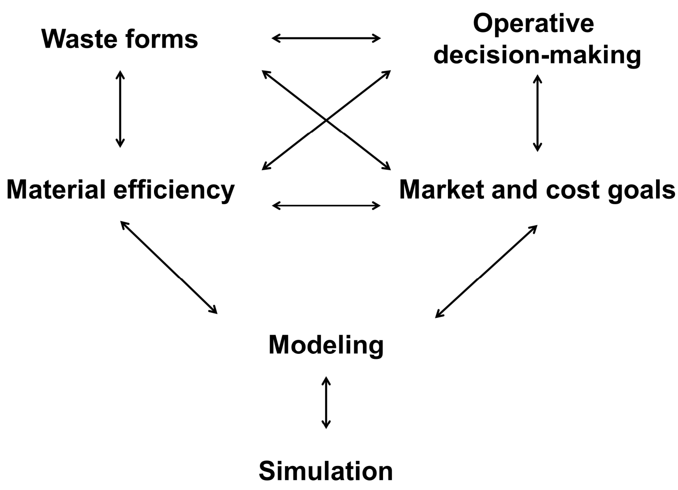



**Figure 7: Reference framework**

## 1.6 Structure of This Work

To answer the research question, this work first describes the framework of consideration and defines the utilized terminology, as shown in Figure 8. The author's understanding of industrial production and operations management (OM) is presented in 2.1. Section 2.2 provides background information on the uses of materials in production systems and common material waste forms, before deriving a definition for factory material efficiency in Section 2.3.

With the framework established, Section 3 examines the challenges of improving material efficiency at the factory level from two perspectives: the obstacles commonly faced by practitioners in the industry, based on the analysis of industry surveys, and the complexity of material waste causation from a technical standpoint. These two aspects form the basis for a list of solution requirements from a business perspective and a technical/physical perspective respectively. Based on the solution requirements, the most suitable methodological approach is selected, dynamic production simulation. The deficits of similar approaches to analyse, predict, and improve material efficiency at an aggregate factory level are demonstrated in Section 4, to crystalize a concrete need for research and develop specifications for the solution. Focus is placed on synthesis approaches following the intended methodological approach, dynamic production simulation.

After identifying two core deficits of the previous works: first, the lack of consideration for the causality of diverse waste flows in a manufacturing system and second, the application of energy-efficiency-based approaches to energy material efficiency modelling, Section 5 investigates the unique properties of material waste occurrence in the factory through an extensive Ishikawa-analysis. The author classifies the influence factors effecting material waste into four categories: those increasing the frequency of material-wasting activities, those increasing the duration of material-wasting activities, those linking material waste to activities, and those increasing the material waste quantity per activity. Based on this finding, the author investigates the relevance and completeness of modelling structures, e.g. machine operating states for material efficiency.

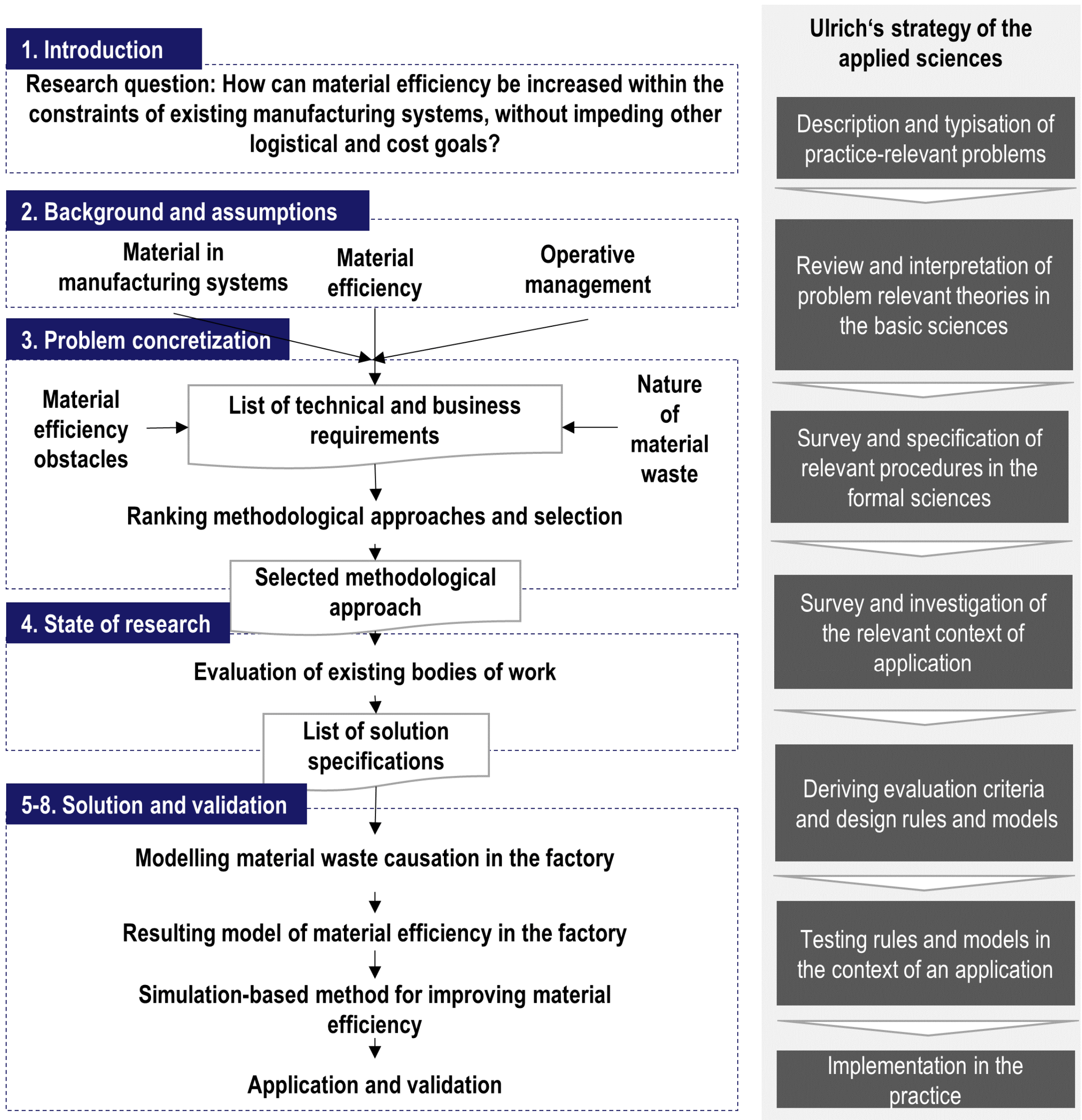



**Figure 8: Thesis structure in accordance with Ulrich's theory of the applied sciences**

Based on the gained understanding of material waste causality, a model for material efficiency at the aggregate factory level is modelled in Section 6, and the mechanisms for reducing total accumulated waste, while maintaining throughput are demonstrated.

Finally, a holistic method for evaluating the effectiveness of material efficiency activities is presented in Section 7, based on system simulation, visualization, and systematic derivation of improvement measures. Application in three industrial settings validates the solution and highlights the strengths and weaknesses of the method (see Section 8). A critical review closes this thesis in Section 9 along with an outlook to future research topics (see Section 10).

# 2 Theoretical Background

In the following sections, definitions and constraints for the investigated system refine the framework of this thesis. Section 2.1 first clarifies the understanding of manufacturing systems and OM in this work. Secondly, this section constructs the limits of operative factory management authority, or in other words, the0 elements of the manufacturing system can be changed through operative decisions in existing manufacturing systems.

Section 2.2 defines the term “materials” in the sense of a manufacturing system and demonstrates the existing classification structures for material flows and material waste.

The subsequent Section 2.3 positions the concept of material efficiency in the factory system within the global definition of material efficiency. The author then derives equations for factory material efficiency and material cost efficiency.

## 2.1 Manufacturing

The following section serves to establish the components and constraints of an existing production system and the scope of OM.

Section 2.1.1 defines manufacturing systems, differentiating them from smaller workshops and supply chains. The potential factors of the production systems, the types of processes that take place, and the nature of production processes are briefly addressed. Building on these basics, the author describes classification criteria for production systems in 2.1.2, to establish the range of production types that are considered in the developed method.

In Section 2.1.3 OM is defined and differentiated from the tactical and strategic decision-making levels. Building on this definition, the goal systems of OM are described in 2.1.3.1. The means with which operative management can steer the production system to reach these goals are described in the final Section 2.1.3.2.

### 2.1.1 Manufacturing Systems

Manufacturing systems distinguish themselves from smaller workshops and service centers through the production of goods at an industrial scale with a strong division of work and a high degree of mechanization (Müller 2009, pp. 35). Production systems encompass technical, social, economic, and environmental activity units, functioning to fulfilling market demands (Westkämper 2006, pp. 24). Production systems add value by combining production factors, such as labor, material, energy, and technical equipment to transform a subset of these production factors (material and energy) into desired products (Gutenberg 1951, pp. 3). However, along with the production of desired products, both unavoidable as well as avoidable outputs are created (i.e. scrap, waste, exhaust heat, etc.) (Westkämper 2006, pp. 196; Schenk et al. 2010, pp. 5). Figure 9 demonstrates the transformation of material and energy into desired and unwanted outputs, an overview of the production factors (Dyckhoff 2010, pp. 17). To characterize all manufacturing systems, Dyckhoff notes that two transformations may take place — the production of desired goods, as well as the disposal or reduction of substances, with the intention of reducing the toxicity or unpleasantness of input waste products and therefore expanding his definition to describe recycling and waste-processing centers.

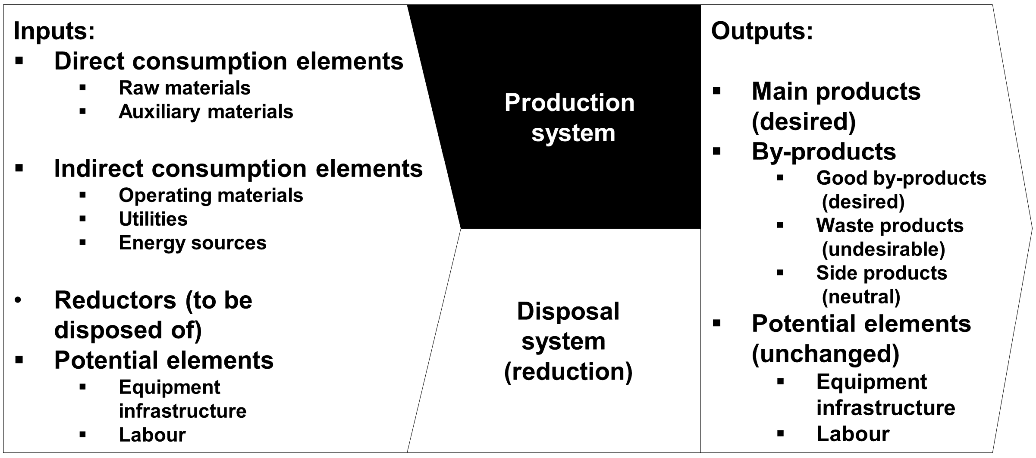



**Figure 9: Factory inputs and outputs (Dyckhoff 2010, pp. 17–19)**

The term, "production processes" describes a set of interrelated activities within the manufacturing system which may or may not contribute to the transformation process, and therefore may or may not "add value" to the system inputs. Examples of production processes include the transformation of inputs through chemical or mechanical means, input combination, transport, control, measurement, or storage, while only transformation and combination processes are considered value-adding. Within the parceled goods industry, most transformation and combination processes can also be termed "Fabrication processes" and fit the classification scheme presented in DIN 8580, with the exception of the chemical transformation of substances. DIN 8580 categorizes fabrication processes by their respective creation, preservation, reduction, or increase of material cohesion, as shown in Figure 10. Forming processes seek to bring cohesion to a shapeless bulk material, forming and heat treatment maintain material cohesion to withstand future loads, while cutting and more generally, subtractive processes reduce cohesion. Joining and coating processes, frequently seen in assembly processes, increase cohesion.

<table>
<tr><th>Create cohesion</th><th>Preserve cohesion</th><th>Reduce cohesion</th><th colspan="2">Increase cohesion</th></tr>
<tr><td rowspan="4">1. Primary shaping</td><td colspan="3">Shape-changing</td><td rowspan="4">5. Secondary shaping</td></tr>
<tr><td>2. Primary shaping</td><td>3. Cutting</td><td>4. Joining</td></tr>
<tr><td colspan="3">6. Changing of Material Properties</td></tr>
<tr><td>Rearrangement of material particles</td><td>Elimination of material particles</td><td>Addition of material particles</td></tr>
</table>

**Figure 10: Classification of fabrication processes by DIN 8580**

Most complex products require the application of multiple transformation and combination processes in a specific order, known as a process chain or workflow, which takes place at either a single production site or multiple production sites.

### 2.1.2 Classification

Manufacturing systems are frequently classified by their material flow structure, repetition, and spatial and organizational form.

**Material flow structure**

The tendency of material flows to diverge in a production system, converge (i.e. multiple subassemblies are assembled), neither (often called 'smooth' production) or both, results from the chemical and physical characteristics of the inputs, as well as the utilized technologies to create a desired product. Therefore, the convergence or divergence describes an inherent trait of a given manufacturing system that can only be changed by adjusting its potential factors.

Divergent material flows (also known as joint production), where a transformation process splits the material flow into the main flow (the desired product) and a coupled product or byproduct of significant mass or value, present the challenge of synchronizing the demands of two markets or coordinating a regulation-conform disposal. Subtractive processes, where chips and small amounts of trim loss occur are generally regarded as non-divergent.

**Degree of repetition**

The manufactured product volumes and the number of unique product variants in the product volumes determine how frequently identical processes and workflows can be performed within a given machine structure. Single production describes the production of a unique product considering special customer requests; serial production, a limited number of products in a planned time period, with setups of the production system to produce different product variants (cars, furniture); and at higher volumes, mass production (electronics, foods) (Westkämper 2006, pp. 199; Dyckhoff 2010, pp. 25). The degree of repetition influences the required labor qualification, the amount of time spend on setups, as well as the potential for automation.

**Organizational structure**

Organizational structure describes the path a manufacturing job travels through the factory, particularly how many times the product changes hands (division of work), how many times the product changes location (physical arrangement of work stations), and if the product is staged between operations (Westkämper 2006, pp. 198). Examples include job-shop production, where workpieces move from one technology-homogenous work center to the next, where one of several parallel machines processes the workpiece, and the workpiece may return to the work center again for a subsequent processing steps. Other examples include production cells, where one employee completes one order using a number of technologies in close proximity; and continuous flow production, which describes workstations linked through a conveyor belt.

### 2.1.3 Operations Management

Operations management is the function responsible for planning and controlling production in order to produce the correct product in type, quantity, quality, at the right time and at acceptable costs (Westkämper 2006, pp. 195). Operations management spans multiple levels corresponding to the three different planning horizons in a business environment, particularly strategic, tactical, and operative production management. Strategic production management comprises strategic positioning in technologies, vertical integration, capacity dimensioning, production sites, while tactical production management is concerned with the current product palette, human resources planning, machine purchases, and logistical structures (Dyckhoff 2010, pp. 32). In contrast, operative production management focusses on increasing serviceability, reducing lead times, reducing inventory, and increasing utilization without changing the existing technology, staff, or product structures.

Figure 11 presents the resulting control-loop at the operative level. The actuating variables utilized by production managers to tweak the performance of the system include changes to the number and the timing of produced parts, subassemblies and final products, and the daily activities of production planning and control (PPC).

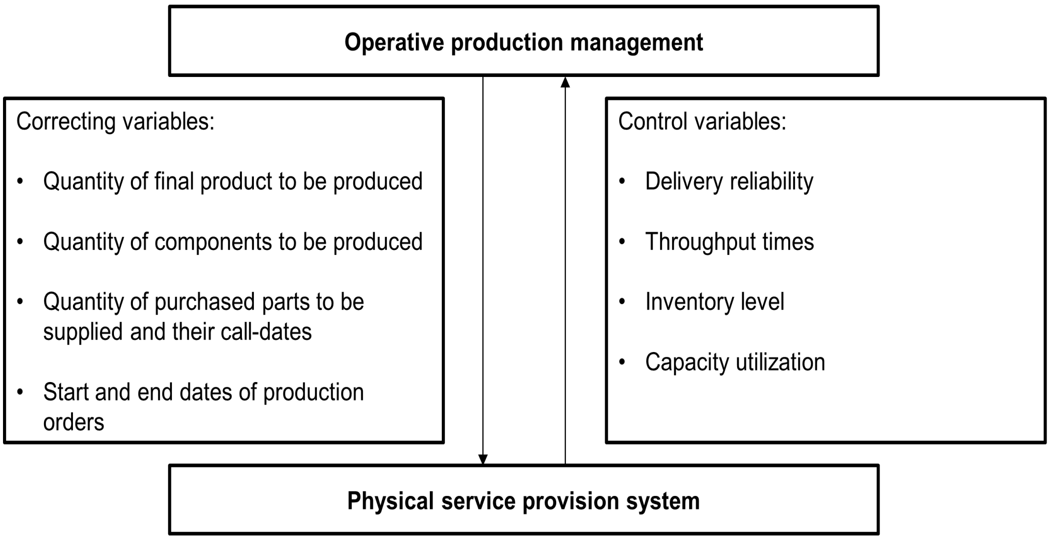



**Figure 11: Control loop of operative production (Dyckhoff 2010, pp. 32)**

#### 2.1.3.1 Goals of Operations Management

Profitability serves as the primary objective of a manufacturing system. While a number of factors outside the realm of production planning and scheduling define the output of the system to a certain extent, production planning and scheduling can significantly influence cost.

The costs that are determined by production planning and control are as follows (Kurbel 2003, pp. 20):

- Setup costs of production equipment
- Idling- and downtime costs
- Inventory costs for raw materials, half-finished goods, and finished goods
- Costs for failure to adhere to delivery dates (contractual penalties)
- Costs from avoiding non-adherence to delivery dates (over time)

However, operations management rarely utilizes pure cost information as a target figure to control production systems for several reasons; i.e., this approach would require current cost data at every planning occasion, and the required cost information includes an opportunity cost characteristic, making it hard to quantify. Alternative target figures are frequently used, which are correlated with cost (Kurbel 2003, pp. 20). Wiendahl's objective system demonstrates two cost goals, to minimize manufacturing cost and capital tie-up costs, and two market or "performance" goals, to minimize delivery reliability and throughput time, as pictured in Figure 12.

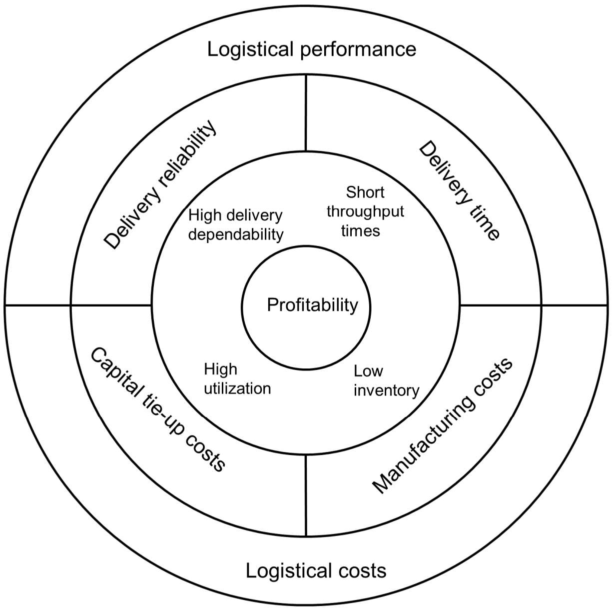



**Figure 12: Manufacturing goal system (Wiendahl 2010, pp. 352)**

Within this objective system, multiple target conflicts exist, which have been deemed to be the dilemma of production scheduling, first identified by Gutenberg (Gutenberg 1951, pp. 216; Gutenberg 1979, pp. 216; Kurbel 2003, pp. 21; Wiendahl 2010, pp. 352).

The first conflict lies between the objectives of short throughput times and high utilization, as maximum machine utilization can only be safeguarded through high levels of inventory ready to be processed. These high levels of inventory lead to a higher average throughput time.

Secondly attaining high delivery reliability requires available (i.e. unutilized) machine capacity for customer/specific products or high inventory levels for customer-anonymous products, both driving up cost.

For these reasons is impossible to achieve all goals simultaneously (REFA 1991, pp. 39). In the last 50 years however, manufacturers shifted from the primary pursuit of economy goals (low inventory and high utilization) towards market goals (high delivery reliability and short throughput time) (Kurbel 2003, pp. 22; Wiendahl 2010, pp. 352)

#### 2.1.3.2 Production Scheduling as a Corrective Variable

In the following section, the terms ‘production scheduling’ and ‘production control’ are described in the context of the manufacturing system. As many definitions are used in this field, the terminology in the context of this work will be clarified. The REFA differentiates planning from control, describing planning as “a systematic setting of goals, jobs, and the means to reach the goals”, while control describes “the arrangement, supervision, and ensuring that jobs are completed in the correct quantity, at the correct time, in the correct quality, at the correct costs and working conditions (REFA 1991, pp. 39).”

Work management describes a segment of the formal order processing procedure and the link between product development and manufacturing, while today work management encompasses work planning and work scheduling (Eversheim 1989, pp. 2; Wiendahl 2010, pp. 246).

Work planning is concerned with all planning measures to manufacture a product or service with a one-time characteristic. Here the manufacturing processes and equipment are specified and selected, without direct connection to specific order or deadline. Without considering capacity restrictions, the most economical operation is generally preferred. Frequently, work planning is characterized by the following questions (Eversheim 1989, pp. 3; Wiendahl 2010, pp. 246):

- What should be manufactured?
- How should it be manufactured?
- With which equipment should it be manufactured?

In contrast to work planning, work scheduling is concerned with all measures required to complete a concrete order. Similarly, the central questions of work scheduling can be summarized as follows (Eversheim 1989, pp. 3; Wiendahl 2010, pp. 246):

- How many pieces should be made in each time period (lot-sizing, line-balancing, shift schedule)?
- When do the orders, materials, equipment, and manpower need to be provided (order sequencing, synchronization)?
- Where should the order be processed (machine assignment)?
- Who should process the orders (shift planning)?

In this work, only the effects of work scheduling on material efficiency and the levers available to schedulers to improve material efficiency is investigated. Assuming a preexisting production system equipped with machinery and a fixed product range, work scheduling completes the following tasks (Kurbel 2003, pp. 17):

- Which quantities of which products should be planned in a given timeframe (production scheduling)?
- Which quantities of pre-products or half-finished goods are needed for these products (secondary requirement planning)?
- Which quantities of products should be produced in lots/batches?
- At what point in time should the processing and the acquisition of materials take place (scheduling)?
- How can the time requirements be aligned with the available machine capacity (capacity planning)?

## 2.2 Material in Production Systems

At the broadest level, the term "materials" describes both substances, which are pure in chemical composition, and goods, which are assigned a value by a market (Brunner et al. 2003, pp. 37). However, in this work, "material" describes only engineered materials, intended to be transformed into desired products, or nonfuel materials that fulfill a purpose in the manufacturing process. This is in line with Allwood et al.'s delimitation of "material efficiency" from "resource efficiency" discussed in Section 2.3 (Allwood et al. 2011, pp. 362).

In manufacturing systems, engineered materials encompass both the inputs of the factory system, including raw materials and vendor parts, auxiliary materials, operating materials, half-finished goods, finished goods, and material waste. Material differs from equipment and tooling in that it is purchased to be transformed into a desired product or consciously consumed in short time periods, while equipment and tooling are investments, assumed to be unchanged after the production process (Dyckhoff 2010, pp. 17–18).

### 2.2.1 Material Inputs of a Factory System

In cost accounting, material inputs to a production system are classified by their function and value contribution to the product.

Raw material describes substances that contribute significantly to both the product mass and product value (Götze 2010, pp. 28). Raw material is both fabricated into workpieces and assembled to form finished products within the bounds of the factory system, and therefore spends the 'component manufacturing' and 'assembly' phase of its lifecycle in the factory, as shown in Figure 13.

Auxiliary materials contribute a smaller portion of the product mass and product value (Rogalski 2011, pp. 14). The differentiation between auxiliary and raw materials is industry- and product specific; e.g. Paints and surface coatings are generally considered auxiliary material, while precious metal coatings may be considered raw material due to their higher value. Auxiliary materials may or may not be included in the bill of materials. Losses in auxiliary material, unlike raw material are generally not recorded by a quality control function. Often auxiliary material are discarded in a rework process to salvage the raw material. Auxiliary materials are usually joined directly with or applied to the surface of raw materials, and are not the object of value-adding processes themselves, and therefore are merely “assembled” in the factory, as shown in Figure 13.

Commercial goods (e.g. supply parts and accessories) are a form of material in the factory that is sold as an accessory to a finished product or as a compliment to the product platform. These bypass all manufacturing processes, but still flow through the factory for distribution purposes (see Figure 13).

Operating materials, in contrast to both auxiliary and raw materials, are not contained in the finished product (Jasch 2009, pp. 80). However, they ensure smooth and effective processing of raw and auxiliary materials. Examples include lubricants, cleaning solvents, machine filters, and internal packaging materials. These materials may be discarded after a single use or recovered and used multiple times, e.g. cutting fluids. Even if these materials are used multiple times, losses via contact with workpieces or machine parts, as well as loss in function due to aging may occur. Operating materials, in contrast to their raw material and auxiliary material counterparts, uniquely spend their use-phase in the factory (see Figure 13), and are therefore “consumed” in the manufacturing process.

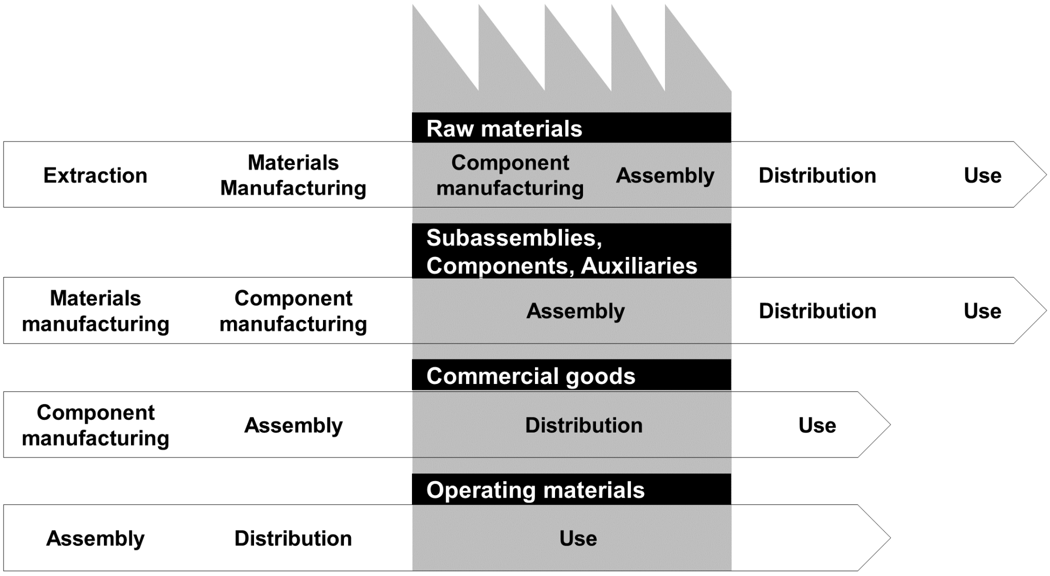



**Figure 13: Stages of the material life cycle spent in the factory**

### 2.2.2 Material Outputs of a Factory System

Coupled with the transformation of the potential factors material and energy into finished goods (desired output), both neutral byproducts and undesired waste products are generated (Dyckhoff 2010, pp. 14). The latter encompasses multiple waste streams in a factory, which have decreased in monetary value, been lost to the atmosphere, or been consumed in the production process.

Oenning's typology of joint production products describes all material waste products of a factory as undesired byproduct in the production of full-value goods in a manufacturing system, and incorporates the cost-accounting material classification as shown in Figure 14. Raw materials that had the potential to become full-value products, and are yet discarded due to errors in the production process (defects) form a different category than residual raw material and byproducts contained in the raw material that never possessed the potential to become a full-value product (Oenning 1997, pp. 50).

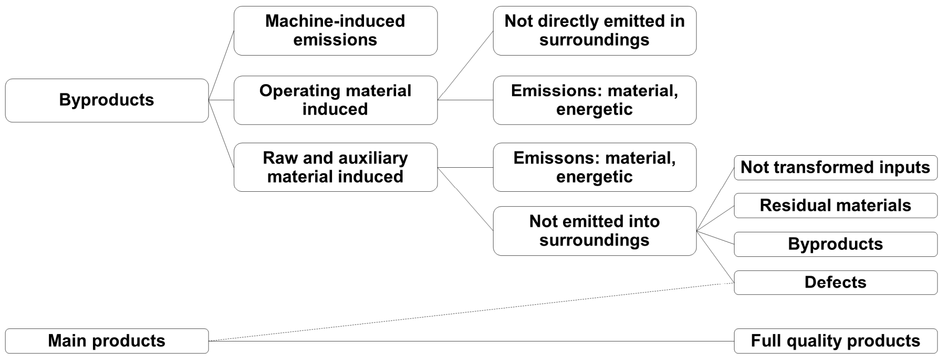



**Figure 14: Typology of coupled industrial products (Oenning 1997, pp. 50)**

Diverse failure modes cause material value-loss. For instance, manufacturers discard raw materials and auxiliary materials as the residuum of a manufacturing process due to contamination or uneconomical retrieval methods (Oenning 1997, pp. 81). Operating materials may be soiled or contaminated while fulfilling their function (e.g. filters) or ejected from the system (e.g. cutting fluids).

Cuts of raw material may be discarded as the unusable remainder of a cutting operation (e.g. trim loss) if they are dimensionally too small for cutting other workpiece geometries. Unsaleable byproducts possess a different chemical composition than the desired (main) product and are therefore removed and discarded in a subtractive process (Oenning 1997, pp. 81). Still other materials undergo physical damage in manufacturing, transport, or storage processes beyond repair or lose value or mass due to material changes without a triggering activity (e.g. spoilage). Technical obsolescence causes immediate loss in material value for products that may still be in the factory.

Erlach and Sheehan's five material waste forms from the $CO_2$ Value Stream Method orders the abovementioned failure modes to the material flow and value-adding phase where they most frequently occur, as shown in Figure 15 (Erlach et al. 2014, pp. 657). Operating materials maintained in a closed-loop reservoir system are distinctively different from single-use operating materials as they undergo value loss through ejection of the material or wear instead of direct consumption.

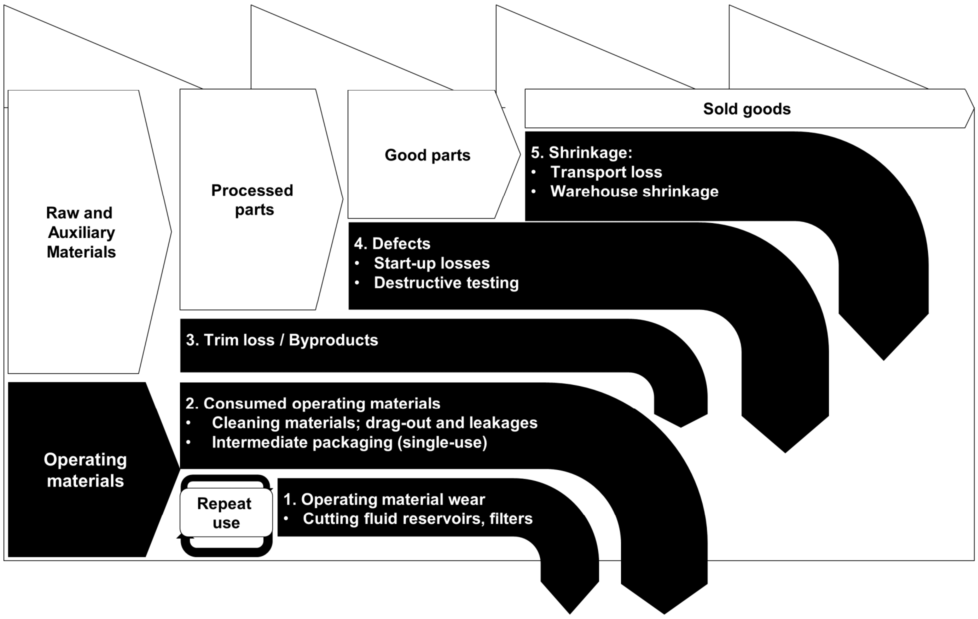



**Figure 15: Waste forms in the factory (Erlach et al. 2014, pp. 657)**

Similar to Oenning's typology, the potential to become a full value product distinguishes defects from subtractive losses and auxiliary material losses. Unsaleable parts describes inventory shrinkage driven by material and product characteristics. Although shrinkage may take place at any point in the value-adding process, finished goods shrinkage entails the loss of raw material value and the added value through the completed manufacturing process.

### 2.2.3 Costs of Material Waste

The cost of material waste scopes not only the purchase price of raw materials but also the backpack of disposal costs, recycling costs, and waste management costs.

Properly sorting material waste and preparing it for disposal requires management functions and a designated area. The cost are partially proportional to the waste volume (e.g. transport costs), while a portion is fixed (management functions, storage capacity) (Fresner et al. 2014, pp. 68). Waste management requirements are driven by environmental law, and therefore outside of company control (Dickens 1994, pp. 40). Depending on material composition, the cost of disposal per mass unit may often exceed the raw material value, especially for hazardous materials (e.g. mercury).

Process defects and inventory shrinkage, where value creation and system capacity are lost through material damage are perceived as the most painful material waste forms. An allocation of these costs to these material waste forms is however unusual in both conventional and material flow cost accounting (MFCA).

## 2.3 Material Efficiency

Efficiency in its simplest terms is the ratio of an output to the input of a system. Over the last twenty years, the definition of material efficiency has evolved from a simple balance of material inputs, to system outputs, to an extension of resource efficiency. Scholars have studied the concept of material efficiency with different frames of reference and on different scales.

Section 2.3.1 provides definitions of material efficiency at a global scale and structures the field of action for material efficiency and their applicability within OM. Section 2.3.2 defines the metric ‘factory material efficiency’.

### 2.3.1 Material Efficiency at a Global Level

Allwood defines material efficiency as all pursuits to deliver human well-being with less material production of high-energy materials; although unlike resource efficiency, only engineered materials are considered (Allwood et al. 2011, pp. 362). Fisher and Worrell provide more restrictive definitions, stating material efficiency only describes how effectively materials are transformed into finished goods, not how effectively they are utilized in the manufacturing process (Fischer 2013, pp. 102), or even considering only how effectively virgin materials are transformed into finished goods (Worrell et al. 1997, pp. 2).

Since this work focuses on all losses of engineered materials losses in the factory system, regardless of their purpose in the factory system, Allwood's definition will be further examined and adapted to the limits factory system.

Scholars have identified action fields to reduce the loss of in the manufacturing of goods and service delivery. The action fields are analyzed for their applicability to the factory system and arranged in the product life cycle model in Figure 16.

a. "Light weighting": designing products with a smaller net material requirement (Peck et al. 2007, pp. 333; Allwood et al. 2013, pp. 5). While reducing the net mass of a product reduces the demand for materials in component manufacturing, it is not a feasible solution for OM without consultation with R&D and sales. Therefore this cannot be considered in this work.
b. Reduce gross material requirements: less subtractive processes, additive manufacturing, geometrically optimized cutting plans (Jackson 1993, pp. 146–147). OM cannot arbitrarily change raw material or process specifications, and therefore this approach is outside their authority.
c. Reduce material use in manufacturing process: reduce the use of operating materials or recirculate operating materials (Jackson 1993, pp. 146–147). This field may be pursued within the factory system, as long as no changes to process or product specifications take place.
d. Re-using components: examining the potential for reuse of end-of-life products for introduction in the same product, fulfilling the same function (Jackson 1993, pp. 146–147; Allwood et al. 2013, pp. 6). Component re-use intensifies the flow of post-consumer product components into assembly centers for re-use. This approach exceeds the gate-to-gate limits of this work and is therefore not further considered.

e. Longer-life products: durable product design or more stable customer preferences to lengthen the life-phase in a sale-business-model (Abdul Rashid 2009, pp. 23; Allwood et al. 2013, pp. 6). Longer product lifespan lessens the demand for products and consequentially the flow of materials from distribution to use. This approach requires consultation with R&D and sales, exceeding operative decision-making.
f. More intense use: utilizing leasing, rental, service business models to provide a service instead of product ownership (Abdul Rashid 2009, pp. 23; Allwood et al. 2013, pp. 6). Leased products intensify the material flow between end-users and distribution (leasing centers). This approach requires strategic change to the business model and thereby exceeds the authority of OM.
g. Improved industrial yield: waste reduction in the production process (Peck et al. 2007, pp. 333). Industrial yield strives not only to decrease raw material losses in manufacturing, but also for the elimination of the flows to disposal as well as to recycling. This approach is within the scope of this work.
h. Reduce virgin portion of material consumption: reintroduce secondary materials in the supply chain (Peck et al. 2007, pp. 333; Abdul Rashid 2009, pp. 23). Shifting the concentration of materials in the system from virgin to recycled or secondary increases the flow of post-consumer waste to materials manufacturing and decreases the demand for extraction. However, this requires a strategic change the manufacturing system (a change in incoming material specification) and exceeds the limits of this work.
i. Less energy intensive materials (Abdul Rashid 2009, pp. 23): using less energy in material manufacturing does not affect the quantity of material flow, but rather its material characteristics. A strategic

change in incoming material specifications is required to follow this strategy.

j. Non-toxic materials (Abdul Rashid 2009, pp. 23): This approach requires a change in incoming material specifications, a strategic decision outside the limits of this work.

k. Less-packaging (Abdul Rashid 2009, pp. 23): Less packaging would lessen the flow of materials from assembly to disposal, therefore exceeding the gate-to gate limits of the factory. However, approaches to limit the use of internal packaging would be within the framework of OM.

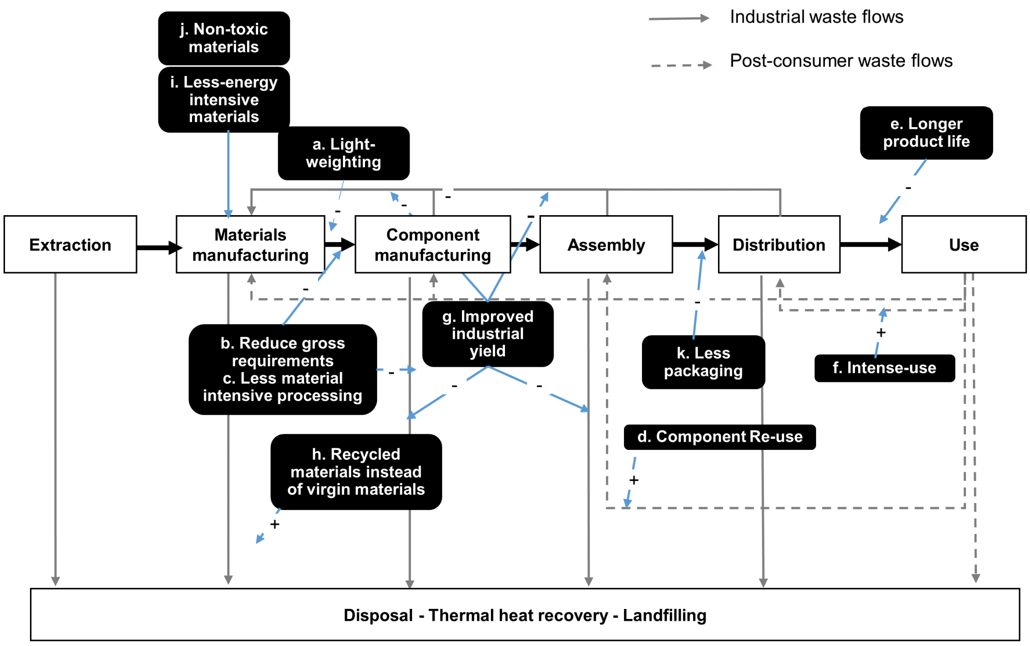



**Figure 16: Material efficiency action fields in the product life cycle**

Examining Figure 16, the action fields form four broader strategies, which roughly align with the recycling hierarchy, as shown in Figure 17. Ideally, it would be possible to eliminate material waste at all process levels by eliminating society's demand for material goods (strategy I). This strategy scopes the action fields more intense product use, longer product life, and less packaging, as material goods circulate through the use and distribution phases infinitely. If strategy I is not possible (e.g. lacks consumer acceptance), strategy II aims to reduce consumer demand for goods from raw virgin materials, therefore lessening the demand for material extraction. This includes the approaches of light-weighting, component re-use, and using recycled materials in manufacturing. Unlike the first two strategies, strategy III assumes an unchanged consumer demand for material goods and focusses on lessening the demand for material extraction and materials manufacturing by reducing the waste caused by these process stages. The fields of action include reducing gross material requirements, using less material intensive manufacturing processes, and improving industrial yield. Strategy IV seeks to reduce the environmental repercussions through material substitution, including using less toxic materials and less energy intensive materials.

The application of these four strategies results in a less intense, loss-free material flow to the consumer or service provider and the reintroduction of end-of life products as late in the supply chain as possible. This vision is in-line with the circular economy concept; however, this thesis will focus on strategy III, since it is the only strategy compatible with set product program and process specifications.

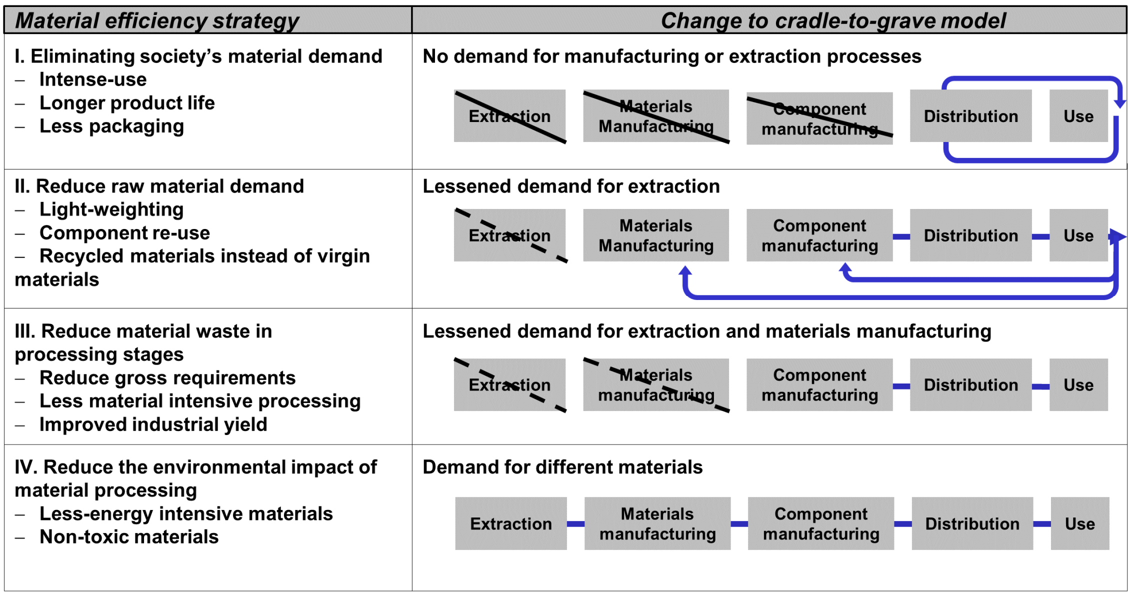



**Figure 17: Material efficiency strategies at a global level**

### 2.3.2 Measuring Factory Material Efficiency

Analogous to the different material efficiency strategies, scholars have defined the metric “material efficiency” differently in the product frame of reference and the process frame of reference.

In accordance with strategy I and strategy II, Peck et al., Allwood et al., and Cooper et al. define the material efficiency mathematically as the quantity of a particular material needed to produce a particular product or service, or more specifically the quantity of virgin natural resources required (Peck et al. 2007, pp. 333; Allwood et al. 2011, pp. 365–366; Cooper et al. 2016, pp. 54). Peck’s definition describes the gross material quantity needed to produce a product, including the material contained in the finished product. One weakness of the metric is the inclusion of both the net material requirement (the material in the final product) and the material losses in manufacturing. If two similar products are compared, it will not be clear if one has a poorer material efficiency due to its heavier design or the inefficiencies of the manufacturing process. Additionally, since the gross material quantity is not normalized against the net material quantity or weight of the finished product, the room for opportunity in light product design and in efficient operations is unclear. If only virgin materials are counted, a third dimension of complexity is added is to the metric, resulting in unclear comparisons of products and production facilities. Rashid alternatively presents a formula in line with strategy III, defining material efficiency as the ratio of the output of products to the input of raw materials (Abdul Rashid 2009, pp. 36). Rashid’s definition can be interpreted as the sum of all raw materials utilized, including operating material losses, to the output finished goods. The metric describes the ability of the selected manufacturing system to prevent quality defects, reduce trim loss though nesting software, or minimize lubricant leakages. Therefore, the metric can be scaled and applied to different levels of the factory, from process level to supply chain level. However, Rashid does not offer insight to the multi-material paradigm, particularly how to reflect the performance of the production system in a single metric if more than one material is used, e.g. plastics and metals.

In manufacturing practices, detailed metrics are utilized in accordance with strategy III. Gobetto presents ‘direct material utilization degree’, defined as the net material requirement (based on product design) to the gross material requirements (including the shortcomings of the transformation process) and auxiliary materials productivity, the quantity of transformed product/auxiliary materials used (Gobetto 2014, pp. 14). Unlike Rashid’s definition, Gobetto specifically addresses the flows of auxiliary or operating materials, without including them in the same metric.

In this work, the limits of the system are set to the walls of the factory (or gate-to-gate); therefore, material efficiency (ME) is defined as the sum the material leaving the factory as a full-value product to the total material output of the factory, as shown in Eq. 1. This is only valid under the assumption that the material waste is homogenous in composition.

$$ME = \frac{Mass_{finished\ goods}}{Mass_{finished\ goods} + Mass_{waste}} \qquad (1)$$

However, since this definition sets mass units of material equal it is unsuitable for measuring the material efficiency of multi-material systems. To account for disparities in material value, Material cost efficiency (MCE), is defined in Eq. 2, as the raw material value of the finished goods produced in a time period, in relation to the raw material value of all material outputs of the system in the same time period. This assumes that the considered time period is adequately long to account for extraordinary circumstances, e.g. collection and disposal of warehouse shrinkage on a production holiday.

$$MCE = \frac{Raw\ material\ value_{finished\ goods}}{Raw\ material\ value_{finished\ goods} + Raw\ material\ value_{waste}} \qquad (2)$$

Unlike Rashid's definition, the portion of the final product value due to value creation through machining, manual labor, and energy expenditure is not considered.

# 3 Problem Concretization

Developing a practice-relevant method to improve material efficiency at the factory level requires both knowledge of the obstacles that companies face when implementing material efficiency activities, as well as a sound understanding of the causality of material waste in the factory.

To ensure the solution is grounded these two aspects, the author first derives solution requirements from a business perspective from industry surveys in Section 3.1. In Section 3.2, the author derives requirements on the system boundaries and the scope of the model to accurately depict the occurrence of material waste at the factory level from a technical perspective. In Section 3.3, the combined list of requirements serves as evaluation criteria to select the best-suited methodological approach from those previously used in this field. In the following chapter, specific publications utilizing the selected methodological approach are evaluated based on the solution requirements. This procedure establishes the deficits of the state of research in this field and provides insight on the necessary components and design of the developed solution, resulting in the formulation of solution specifications, as shown in Figure 18.

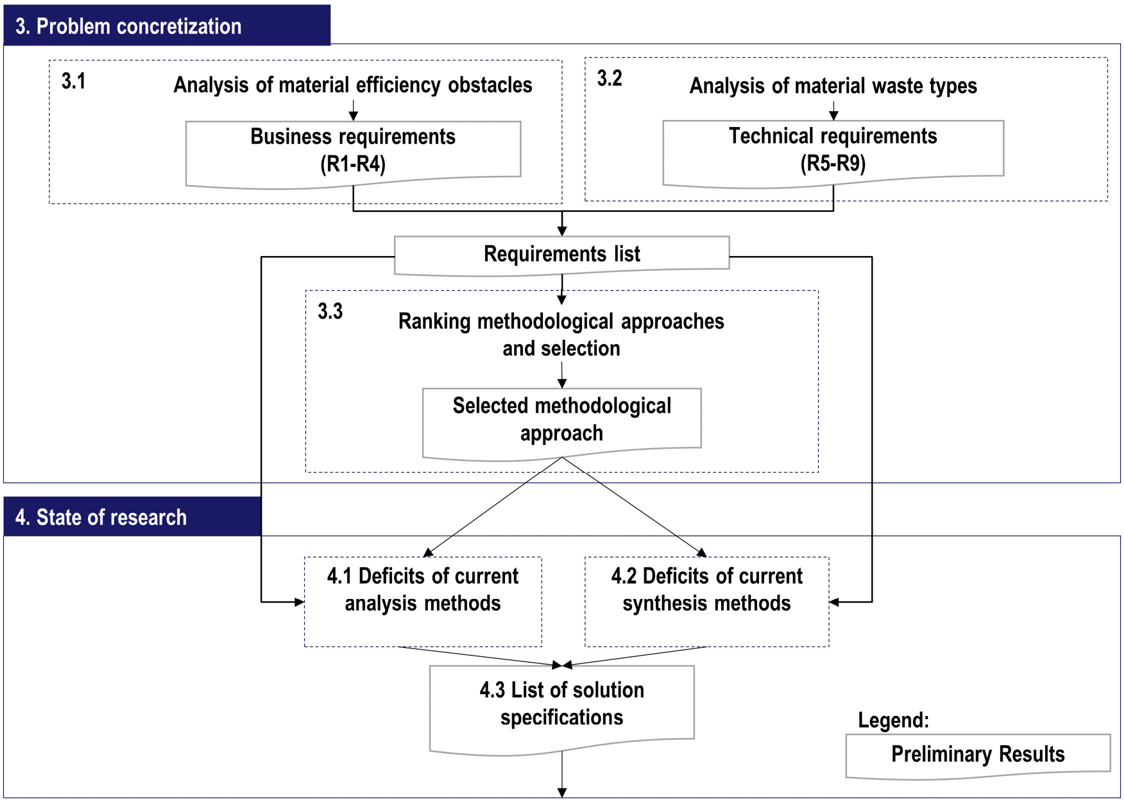



**Figure 18: Approach to define solution specifications**

## 3.1 Requirements from a Business Perspective

Recent industry surveys conducted by Baron et al.(Baron et al. 2005), Biebeler (Biebeler 2014b), Rashid (Abdul Rashid 2009), Schmidt et al. (Schmidt ), and Wied et al. (Wied et al. 2009) revealed obstacles affecting the manufacturing industries in Germany and the U.K., hindering them from increasing their material efficiency. The survey participants represent small, mid-size, and large companies in multiple manufacturing sectors, including automotive, machinery and equipment, electronics, construction material, glass, and others. The most commonly addressed obstacles in these studies are summarized below:

**I. Conflicting goals** (Wied et al. 2009, pp. 47)

Material-efficient solutions may conflict with other goals (profitability, machine utilization, throughput time, etc.).

This obstacle demonstrates the lack of decision-making support methods to predict the benefits and trade-offs of implementing material efficiency.

**II. Too little information for decision-making and prioritization** (Abdul Rashid 2009, pp. 218; Biebeler 2014b, pp. 75)

Companies lack information to make informed decisions to navigate the abovementioned goal-conflicts or to prioritize material efficiency in a set of goals.

This obstacle indicates deficits in the understanding of the causation of material waste and the interdependencies within the production system between material efficiency and other cost-and market goals.

**III. Measurement and target-setting** (Abdul Rashid 2009, pp. 218)

Even if material efficiency is recognized as a high priority, it is difficult to measure material efficiency in a multiple material facility with a multitude of material waste forms. The potential for improvement within existing facilities may be unknown; therefore, setting an achievable, measurable goal is unlikely.

This obstacle presents the preliminary need for a material efficiency measuring method, and not only a method to improve material efficiency.

**IV. Lack of time or human resources** (Baron et al. 2005, pp. 62; Abdul Rashid 2009, pp. 218; Wied et al. 2009, pp. 47; Biebeler 2014b, pp. 75)

Managers, particularly in small or mid-size companies, lack the time to anchor material efficiency initiatives or make informed decisions about material efficiency. Similarly, companies may lack qualified staff to handle the planning and operationalization of material efficiency strategies (Baron et al. 2005, pp. 62).

This obstacle underlines the need for a low-effort method with a well-defined data collection procedure.

**V. Complacent attitudes for companies within industry norm** (Baron et al. 2005, pp. 62)

Baron's interviews with industry leaders revealed an attitude of complacency with regard to material efficiency, as long as the material cost percentage is within the normal range for their respective branch (Baron et al. 2005, pp. 62). Logic serves that costs will be cut where companies suspect they are performing poorly against the competition, not where they are in the normal cost range. Since few companies have focused on cutting material costs, there is little pressure to improve.

Though a method for increasing material efficiency cannot remedy this attitude alone, a method that demonstrates the material-saving effects of small changes in operative decision-making may catch the interest of companies eager to profit from low-hanging fruits.

**VI. Technology not available/ Machinery industry has cut R&D** (Baron et al. 2005, pp. 62; Wied et al. 2009, pp. 47; Biebeler 2014b, pp. 75)

Some material waste forms are fixed for a process technology. Depending on the application, no process alternatives may exist, which may be attributed to the constraints of the product design (Abdul Rashid 2009, pp. 218). The unwillingness of machine builders to invest in R&D may also contribute to the lack of technical alternatives (Baron et al. 2005, pp. 62).

If a technology-induced material waste form represents the majority of the material waste costs for a manufacturing system, companies may become frustrated and perceive material efficiency as an unachievable goal, overlooking influencable material waste forms, which are smaller in mass. Therefore it is important for the system to distinguish between the material waste that in attributed to the utilized technologies, and the portion that can be controlled though better operative decision-making.

**VII. High investment/Long amortization period** (Wied et al. 2009, pp. 47; Biebeler 2014a, pp. 75)

If alternative process technology is available, the required capital investment may deter manufacturers from pursuing the technology change. Additionally, depending on the achievable material savings, its amortization period may be too long to be financially viable.

Analogous to the previous obstacle, companies with technology-attributed material waste, where a solution is available but not financially viable, may discount material efficiency as unachievable and ignore smaller, yet more easily influencable material waste forms. The method must demonstrate which share of material waste can be prevented within the factory system.

**VIII. Too high quality standards** (Baron et al. 2005, pp. 62)

Manufacturers have set unattainably tight specifications for e.g. part surface quality, leading to high defect rates (Baron et al. 2005).

This serves as an example of the disparity between customer requirements and readiness of process technologies. While the developed method cannot redefine market demand or the specifications of products to meet that demand, the method should present which role quality defects play in the overall material efficiency of the factory.

**IX. Customer-driven product variety** product customization / high product variety / short product lifecycles (Baron et al. 2005, pp. 62; Abdul Rashid 2009, pp. 218)

Manufacturers have been under pressure for the last 50 years to meet increasingly diversified customer demand, at the cost of any economies of scale and more specifically material efficiency. This push from the market has led to more engineer-to-order (individual) production, making it virtually impossible to fully utilize stock sheets in cutting operations, and causing frequent machine setups and frequent periods of unstable, ramp-up production. Shorter product lifecycles, another trend, inhibit manufacturers from benefitting from process learning curves.

**X. Organizational barriers** (Abdul Rashid 2009, pp. 218; Wied et al. 2009, pp. 47; Biebeler 2014b, pp. 75)

Most companies lack a centralized function to execute and monitor a variety of material saving measures. Material efficiency may be championed either by quality management (defects), manufacturing (trim loss), warehouse management (for transport losses and inventory shrinkage), maintenance (lubricants), or an environmental management function, resulting in uncoordinated and potentially conflicting activities (Shahbazi 2015, pp. 73).

For that reason, the method must be easy to learn for both users with and without technical backgrounds. A straightforward procedure for practical application should specify how the required data is to be collected and prepared.

After reviewing the obstacles addressed in industry surveys, requirements from a business perspective were defined, keeping the scope of this work in mind (see 1.3 and 1.4).

Obstacles I and II address the need for clarity regarding the benefits of material efficiency activities and the trade-offs in cost and market goals. Obstacle III highlights the need for a target-setting procedure. Obstacles VI and VII confirm the importance of investigating the potential to increase material efficiency within the constraints of the existing system, especially in cases where technologies are not yet available or not viable for industrial application.

In order to set reasonable improvement goals, the method should be able to estimate the potential material savings within the constraints of the current manufacturing system. The method should be able to model accumulated material waste while monitoring other system performance metrics. Through scenario building, the effects of material efficiency activities on each material waste form and system performance are demonstrated and potentially conflicting goals are identified. Therefore the following two requirements are defined:

R1. Estimate potential cost savings within current technology limits

R2: Recommend material efficiency activities considering goal-conflicts

Obstacles IV, V, and X describe the need for a low-effort solution that enables the user to collect the relevant data quickly from relevant departments, and provides results after a short computation time. The method should be easy to learn, accessible to managers at low cost, and provide decision support within an acceptable data processing time. Therefore the following solution requirement is defined:

R3: Fast and low-effort

Obstacle IX describes the need for an easily repeatable method for different scenarios for a system with a high-variety, frequently updated product spectrum. This indicates that the required data must be easily collected, even for new product variants that are not yet in series production. To address this need, the following requirement is defined:

R4: Adaptable to fast-changing product spectrums

Figure 19 depicts the clustering of the obstacles and the derivation of four solution requirements.

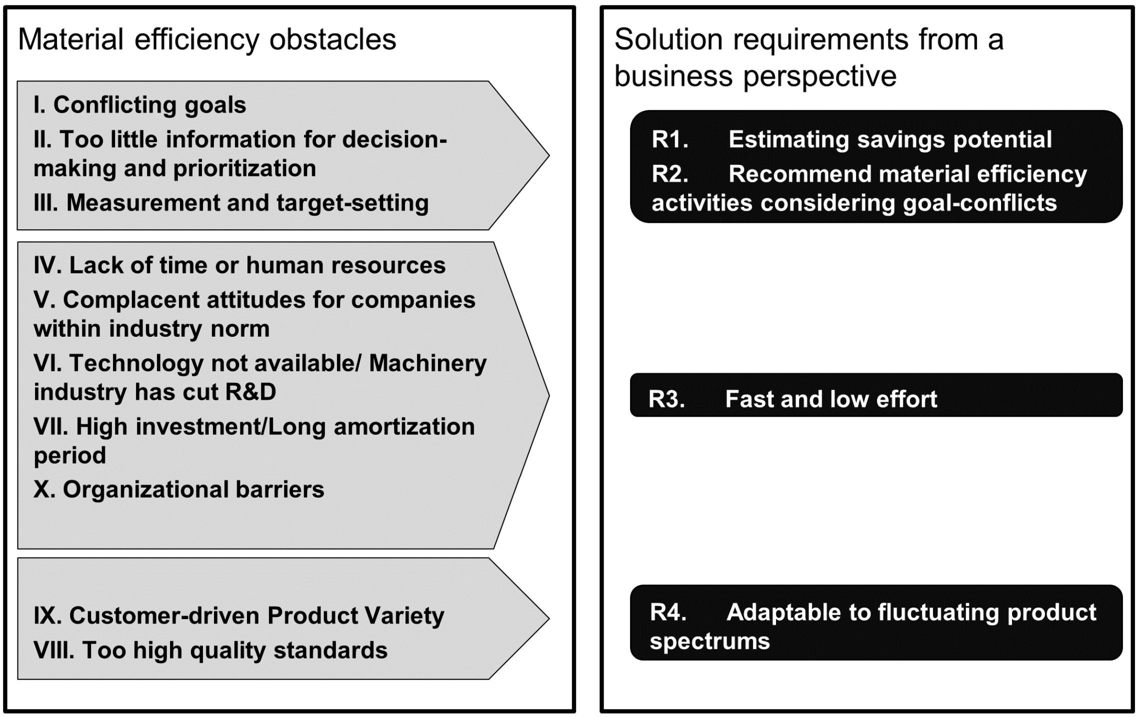



**Figure 19: Formulation of business requirements**

## 3.2 Requirements from a Technical Perspective

In addition to addressing the specific challenges manufacturers face when improving material efficiency, it is critical that developed method accurately model the occurrence of material waste under different production conditions. The set of requirements will be defined using the five W's method, commonly used in journalism and in gathering IT system requirements, to ensure every aspect of the material occurrence phenomenon is addressed.
The five W method, asks questions starting with the five interrogative words: what, who, where, when, and why?
These are usually formulated into the following questions, displayed below in **bold.**
**What happens?**
Material undergoes an undesired transformation or cannot economically be retrieved and reused, and therefore loses its utility at a single point in the production system. Across all material types in the factory and in numerous processes this phenomenon occurs, amounting to the total material waste cost. Therefore it is clear that the phenomenon must model material waste flows, and consider a system at the aggregate level, frequently called the multi-machine level. The following requirements have been identified:
R5. Consider multiple machines in process chains and their spatial relationships
R6. Multiple material flows and waste forms
**When does it happen? Why does it take place?**
The transformation or change in status is linked with a planned activity, an unplanned event. Some of the planned activities, which trigger material waste, comprise the core dynamic behavior of a production system, such as setting up and starting up a machine to fulfil a new order. Unplanned events like

machine errors, idling, and employee errors, may be triggered directly or indirectly by the dynamic behavior of the production system.

R7. Represent dynamic behavior

**Where does it take place?**

The transformation to material waste physically takes place in both direct and indirect (e.g. storage facilities) in the factory, frequently for different reasons (e.g. process defects and inventory deterioration) (Slawik 2012, pp. 93). The linked activities can be either discrete or continuous. Some material waste cannot be attributed to an active process, but rather an unplanned event, or the result of a continuous natural process (e.g. spoilage). Therefore the following requirement is defined:

R8. Model both value-adding and non-value adding, discrete and continuous processes

**Who is involved?**

A number of actors may play a role, including mechanized processes (machines), employees (man), material attributes, methods (management policies), or ambient conditions. Employee influence and the influence of ambient conditions in the consumption of materials cannot be ignored. While these factors may not trigger a material consuming activity, they may increase the material waste occurring per activity. Studies have shown low employee motivation and cost-consciousness can increase the amount of material waste in some activities by up to 400% (Nolte 1998, pp. 107). Therefore the following requirement is defined:

R9. Holistic modelling of material waste causation

The formulation of the technical requirements is summarized in Figure 20.

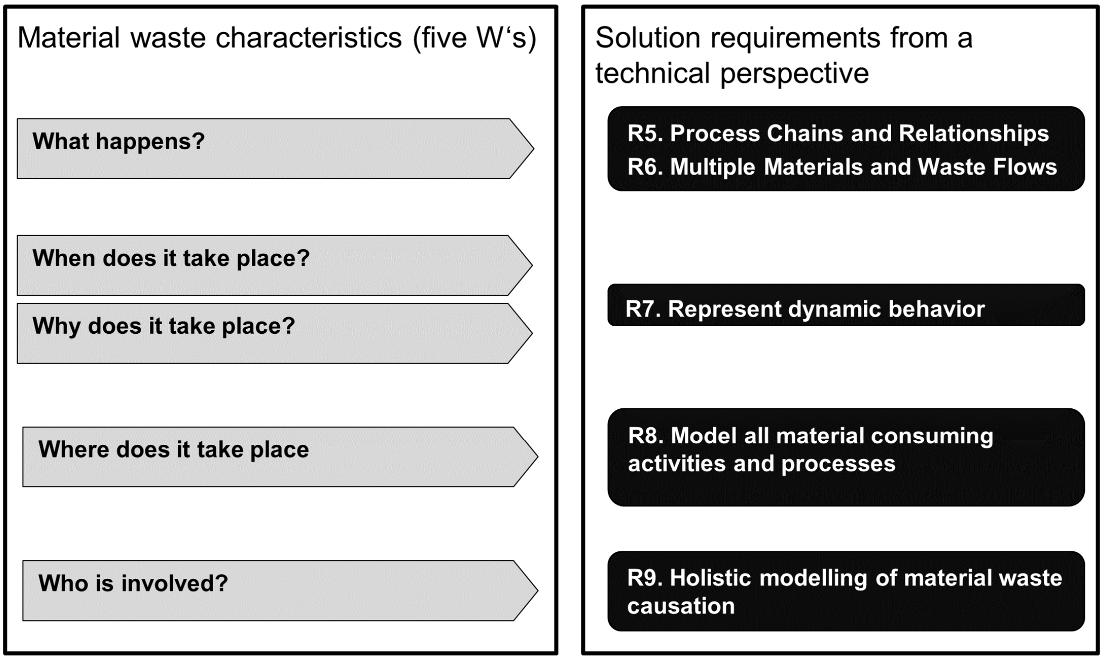



**Figure 20: Formulation of technical requirements**

## 3.3 Selecting a Methodological Approach

To select the best-suited methodological approach from the formal sciences to pursue increasing material efficiency at factory level, a two-step ranking procedure is carried out in the following section.

In the first step, four methodological approaches, which have been applied to similar problem formulations, are described and compared. These include static calculations of material consumption based on measured data, fuzzy logic models, artificial neural networks (ANN), and dynamic production simulation. For each methodological approach, examples of their application for similar problem formulations, including reducing energy consumption and the emittance of pollutants at manufacturing system level, are described. The four approaches are then ranked in order of their suitability to fulfill each solution requirement defined in Section 3.

In a second step, the best-suited methodological approach is then refined by comparing different variations of this approach, and selecting the best-suited variation for this problem formulation. Section 4 demonstrates the state of research only for methods that seek to increase material efficiency using the selected methodological approach.

### 3.3.1 Suitability of Existing Methodological Approaches

In the last 30 years, different methods have been used to predict the accumulation of factory waste and support waste minimization decisions at the factory level, mostly for applications in the chemical and process industries. The existing approaches can be classified into one of the categories described below.

**Static calculations:** Material flow analysis (MFA) utilizes the principle of the input-output analysis to balance material and energy flows within a system, featuring the interconnectivity of the material flows and their quantities (Brunner et al. 2003). This method is based on a quantitative survey of the materials and energies going into a transformation process, indicating that the exact quantities of substances required for a certain output must be known. The observation period is generally over multiple years, and at different levels (national, regional, company level) (Brunner et al. 2003). Material flow cost accounting (MFCA) presents an instrument to monetarily evaluated material consumption and utilization in manufacturing processes. An assignment of material types, material quantities, and even energy can be assigned to a part of a process (ISO 14051 2001).

By tracking the scrapped and consumed materials over time with MFA or MFCA, a consumption profile can be determined for each workstation. Combining the consumption data with the respective production schedule (part numbers, lot sizes, run-times) ex post, a profile for each machine and part number can be formed. The consumption profiles can then be superimposed to estimate the material consumption of the entire factory for future production schedules.

However, this approach relies heavily on historical data and assumes there are no interdependencies between workstations. With an adequately large quantity of data sets, static calculation may be sufficient to evaluate the effect of lot-sizing or production sequences in a single process and evaluate improvement measures.

**Fuzzy logic**: Lou et al. present a waste minimization decision support method based on artificial intelligence and fuzzy logic for the multiple waste flows in the electroplating process and its peripheral processes (e.g. sludge treatment) (Luo et al. 1997). Based on an input of process parameters (e.g. flow speed, concentration), the decision support system suggests improvement measures for a given system with an estimation of their effectiveness in reducing different waste forms (e.g. drag out, bath life reduction). This solution requires expertise specific to each manufacturing process and therefore is unsuitable for a generic method for forecasting material consumption.

Musee et al. provides a similar approach for evaluating the effectiveness of improvement measures in wine-making, including process parameters, increasing levels of communication, and changing delivery frequencies (Musee et al. 2010). Similarly, to the abovementioned approach, a predetermined set of improvement measures specific to each technical process is evaluated for a given set of data, making this approach difficult for application in other branches, where the effects of the measures on the system waste forms are unknown.

**Artificial neural networks (ANN):** ANN has been used to support waste minimization decision-making in the process industries by various authors (Huang et al. 1993). Measured material waste data under different process conditions (batch size, sequence) teach the ANN, deriving the significance of a set of influence parameters and allowing the estimation of future material waste creation. Similar to fuzzy logic, the inputs of the system and outputs are analyzed while treating the process as a black box. Therefore if a multiple-process system is considered, the prediction of material consumption for individual consumers is not possible.

**Manufacturing simulations:** Alvandi et al. present a discrete event simulation (DES) in Anylogic$^{TM}$ (Alvandi et al. 2015) to predict the energy consumption and losses in cutting fluid. This work builds on the contributions of Thiede and Haag to predict the energy consumption of a multi-machine production system as a function of machine operating state (Thiede 2012; Haag 2013). In the DES paradigm, passive entities (particularly production jobs or workpieces) travel through a system where they trigger actions (Borshchev 2004, pp. 4). Sheehan et al. presents a simulation model of material waste accumulation over time using the systems dynamics (SD) paradigm in Vensim™ (Sheehan et al. 2016). SD, a continuous modelling paradigm, depicts systems as a set of stocks and flows, handling every entity (jobs, workpieces) in a stock as the same. Hybrid simulation models combining aspects of both systems are also utilized in manufacturing.

Table 3 shows a simple assessment of the suitability of each of the four abovementioned methodological approaches for pursuing the research question, considering the solution requirements. For each requirement, the approach is that best fitting is ranked as 1$^{st}$, followed by the 2$^{nd}$, 3$^{rd}$, and 4$^{th}$ best-fitting options. A simple mean ranking is calculated at the bottom of the figure. High-rankings in no way indicate that a solution exists that fully meets the requirement, but rather that the requirement could be fulfilled following this approach with little effort compared to the alternatives.

Manufacturing simulation ranks highly in all requirements due in part to the availability of commercial software (speed, low effort) and its application in other manufacturing goal conflicts (e.g. energy efficiency vs. flexibility, performance).

Fuzzy logic and ANN fail to assign quantities of material waste to their points of occurrence in multi-machine systems and therefore offer little insight for optimization or recommendations for material efficiency activities. In fuzzy logic and ANN, process-specific data and process expertise are used to determine the metrics that serve as predictors of material waste. It raises the question of whether the approach is suitable for a high-customization, high-variety production.

**Table 3: Suitability of methodological approaches**

| | *Static calculation* | *Fuzzy logic* | *ANN* | *Dynamic simulation* |
|---|---|---|---|---|
| *R1. Estimating savings potential* | 2 | 4 | 3 | 1 |
| *R2. Recommend material efficiency activities considering goal-conflicts* | 2 | 3 | 4 | 1 |
| *R3. Fast and low effort* | 1 | 4 | 3 | 2 |
| *R4. Adaptable to fluctuating product spectrums* | 2 | 4 | 3 | 1 |
| *R5. Consider process chains and spatial relationships* | 2 | 3 | 4 | 1 |
| *R6. Multiple materials* | 2 | 4 | 3 | 1 |
| *R7. Represent dynamic behavior* | 2 | 4 | 3 | 1 |
| *R8. Consider all material consuming activities* | 1 | 4 | 3 | 2 |
| *R9. Holistic modelling of material waste causation* | 2 | 3 | 4 | 1 |
| ***Mean ranking*** | **1,8** | **3,7** | **3,3** | **1,2** |

### 3.3.2 Refining the Methodological Approach

The selected methodological approach, dynamic production simulation, is refined by selecting the best-suited simulation paradigm for the objective of this work. Table 4 summarizes the differences between the most prominent simulation paradigms, DES and SD.

DES models jobs in a manufacturing system as passive entities, which travel through the system, occupying manufacturing resources and queueing. Different entities using the same resources (e.g. product variants) can be tracked through the system and observed over time. Typical goals of a DES manufacturing simulation are to determine the utilization of resources (machine or employee utilization), or throughput times and thereby the logistical performance of the system. Add-on software packages for the commercially successful Plant Simulation™ software have been developed to model the energy consumption of machines over time. DES has been criticized for its inability to accurately approximate continuous behavior in manufacturing systems, particularly at the aggregate levels (Helal 2007, pp. 1–2), and is even deemed "incompatible with the global view" (Lin 1998, pp. 344).

SD is traditionally applied at the macro level to investigate population dynamics, competition on the marketplace, and ecosystems (Borshchev 2004, pp. 3). Mathematically SD simulations are a set of differential equations, with variables modelled as stocks (e.g. city population or the volume of water in a bath), flows (changes in stocks), and auxiliary variables, which determine the values of the flows. SD simulations are generally concerned with the progression of the stock variables over time. Feedback loops and self-amplifying or balancing effects are most easily demonstrated in SD models.

In manufacturing SD models, the manufacturing rate of a process is seen as a flow, emptying the stock of raw material and filling the stock of processed material. Unlike the entities of a DES diagram, the material in an SD flow must be homogeneous. Therefore, multiple, linked SD flows are utilized to model multi-variant production.

Agent-based simulation (AB) is fairly new and has found application in the modelling of systems with independently acting entities in a free environment (e.g. people, companies) that fluctuate between a finite number of states (e.g.

sick, healthy). Neither jobs, nor machines, nor materials in a factory freely switch states in the manner that mimics the intelligent agents of an AB system. For that reason, this paradigm is not considered further.

Examining the first solution requirement, assuming the user is experienced with these simulation methods, a DES and SD simulations can provide an estimate of the material savings potential equally well. Similarly, both approaches can simulate goal-conflicts within manufacturing (e.g. serviceability vs. holding cost). Continuous simulations have slightly longer simulation times, though both are generally in the minutes-range. Therefore both paradigms received the full score in R1-R3. Both approaches can consider logistical and spatial relationships between processes and demonstrate dynamics behavior when correctly structured and parametrized, resulting in equal score in R5 and R7.

SD production simulations bear a weak point when modelling queues and inventory stockpiles. Stocks, accumulated variables influenced by a physical (non-information) inflow and outflow are assumed homogeneous in composition. If multiple variants are produced, the inventory of each product variant needs to be modelled separately. In a system with many and quickly changing product variants, the effort of creating, removing and renaming the stock variables makes system dynamics simulation cumbersome. Therefore R4 is not completely fulfilled by the SD paradigm.

On the other hand, the stock-and flow structure of SD simulation is analogous to the structure of material flow analysis software, *Umberto* (Schmidt 2009, pp. 21). Through this material flow-oriented structure adding and managing multiple material flows is somewhat easier than in a DES software (R6).

Considering all types of material consuming processes described in the previous sections, a continuous SD simulation has the ability to consider both discrete and continuous processes while discrete DES simulations struggle to depict continuous processes. Therefore it is assumed that SD has an advantage in fulfilling R8.

While both approaches can model an infinite number of parameters, SD simulations are particularly useful in modelling of complex causal relationships, e.g. with self-amplifying effects. Therefore it is assumed that SD is better suited for addressing holistic causality (R9).

**Table 4: Suitability of simulation paradigms for material efficiency modelling**

| | *Discrete Event (DES)* | *System Dynamics (SD)* |
|---|---|---|
| *R1. Estimating savings potential* | ● | ● |
| *R2. Recommend material efficiency activities considering goal-conflicts* | ● | ● |
| *R3. Fast and low effort* | ● | ● |
| *R4. Adaptable to fluctuating product spectrums* | ● | ○ |
| *R5. Consider process chains and spatial relationships* | ● | ● |
| *R6. Multiple materials* | ○ | ● |
| *R7. Represent dynamic behavior* | ● | ● |
| *R8. Consider all material consuming activities* | ○ | ● |
| *R9. Holistic modelling of material waste causation* | ○ | ● |

*○= low degree of fulfilment* *●= high degree of fulfilment*

Due to the limitations of a purely discrete event simulation paradigm, a system dynamics based paradigm with hybrid elements is chosen. Because Vensim™ offers system dynamics modelling in addition to a wide array of discrete functions it is selected for the application of the method.

### 3.3.3 Simulation Studies

Simulation studies generally follow a procedure, consisting of problem abstraction, data collection, implementation and validation, followed by a series of experiments and closing with an implementation of the results, as shown in Figure 21. This approach to simulation is utilized in this thesis.

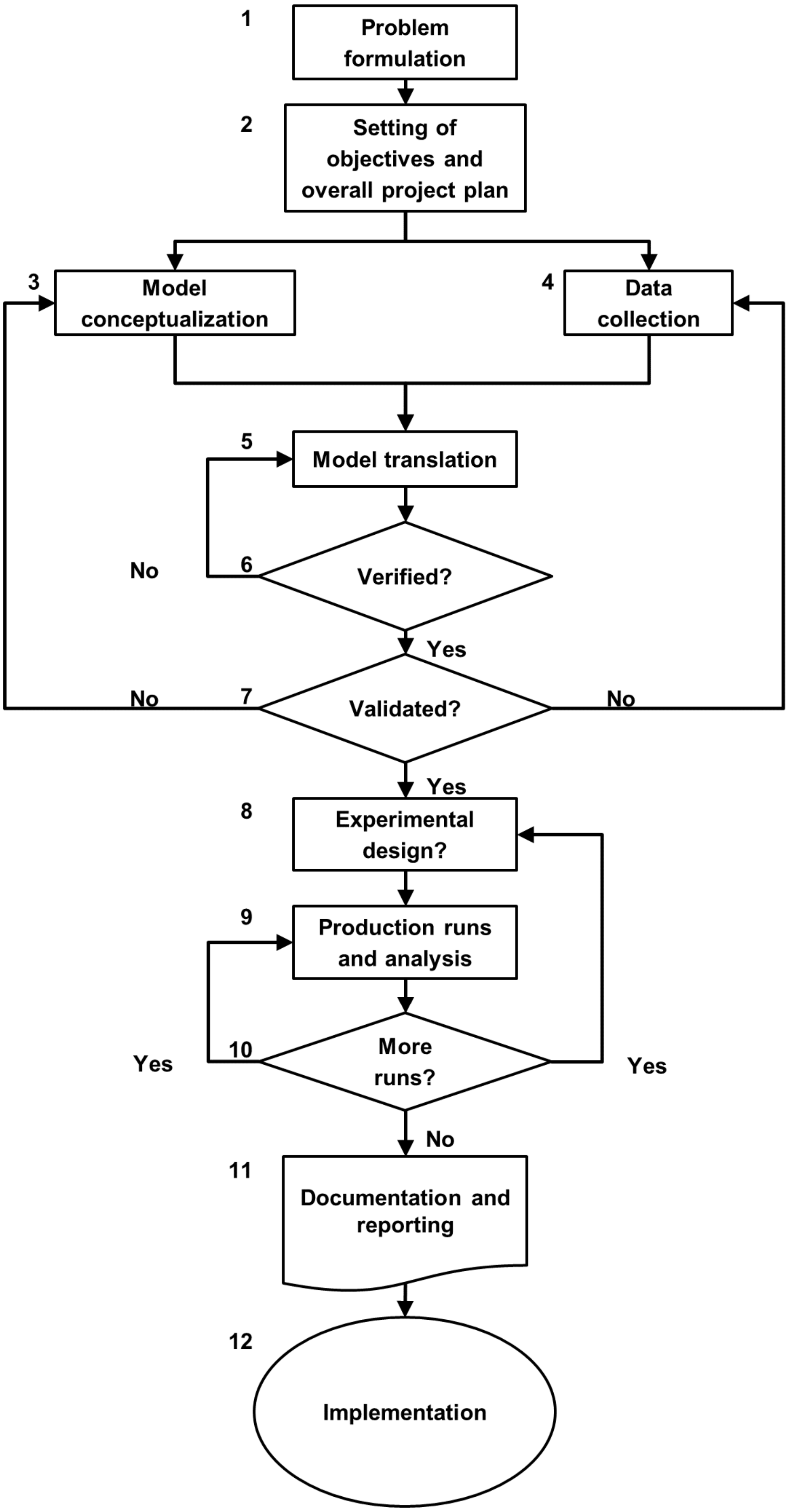



**Figure 21: Procedure of a simulation study (Banks et al. 1996)**

For the preliminary validation of a model that predicts the material efficiency of a system, the validation of historical data will be utilized (e.g. generation of correct material waste values for a given period and correct throughput). Following experimentation in the model, predictive validation is used.
Based on this practical procedure, it is clear that a simulation-based method requires both an analysis portion which collects the relevant data (3 in Figure 21) and structure the model to depict real-world behavior (4 in Figure 21), while the second portion takes on a synthesis character, creating alternative scenarios and recommending a course of action (8-10 in Figure 21). For that reason, the current state of research examines both analysis methods, which collect and structure data for later use in simulation studies, as well as simulation-based synthesis methods in Section 4.

# 4 State of Research

To determine the need for research in the addressed field, a thorough examination of the current literature is required. Because this work investigates a holistic approach to both analyze and improve the material efficiency of a manufacturing system, two types of work will be reviewed. The first type are deemed "analysis methods", whose purpose is to measure the material efficiency of the system and collect all relevant data for improvement. The works in the second literature group are deemed "synthesis methods", whose purpose is to accurately model the system under varying conditions and suggest improvements in material efficiency.

To narrow down the scope of this literature review, only bodies of work fulfilling a set of prerequisites are evaluated in detail.

These prerequisites are:

- Focus within the gate-to-gate limits of the factory: the work's core focus is in factory operations. Literature addressing material consumption in the product use-phase, product recycling, or the supply chain are not considered for this reason.
- Process-chain level: an abundance of research can be found on the simulation of manufacturing processes for better material yield (e.g. FEM, CFD simulations), however the focus of this work is the material efficient operation of the factory system, not parameters of individual processes
- Consider multiple material waste forms: the works should scope at least two material waste forms. A few exceptions are made for works that considered utility-efficiency (e.g. water consumption) and material efficiency

For synthesis methods only:

- Manufacturing simulation-related: the literature work should utilize dynamics simulation to investigate a more material-efficient course of action in manufacturing systems. Mathematical optimization models are not considered.

## 4.1 Analysis Methods

Using the prerequisites above, the author examines methods for collecting and analyzing material consumption data in the factory and summarizes these by type.  After describing the method, the weaknesses and strengths of the method are examined, and finally the method is rated on its suitability to fulfill the requirements defined in 3.1 and 3.2.

### 4.1.1 Input-Output Methods

Input-output analysis (I-O Analysis) requires the sampling of defined input parameters and output parameters over a defined time period. The observations are then depicted quantitatively and qualitatively over a period. If an adequate number of measurements are taken, target values for the input parameters can identified to achieve a desired output value, under a set of fixed conditions. Specific examples are described individually below.

Binding proposes a four-step systematic to measure and decrease material consumption in manufacturing processes: data collection – analysis – solution – and evaluation. The data collection survey the inputs and outputs of the process in quantity and quality, distinguishing between direct and indirect materials (Binding 1988, pp. 42). Binding relies on a list of classical material efficiency instruments for improvement, which are evaluated by a cost-benefit analysis.

Slawik (Slawik 2012) suggests a material flow analysis based method for measuring and improving the material efficiency of manufacturing systems. After data collection, technical and organizational measures are defined using list of predefined causes and sub-causes for the observed material waste forms. The list of causes is based on an European SME survey (Slawik 2012, pp. 96).

Material flow analysis (MFA) utilizes the principle of the input-output analysis to balance material and energy flows within a system, featuring the interconnectivity of the material flows and their quantities (Brunner et al. 2003). This method builds on a quantitative survey of the materials and energy sources going into a transformation process, requiring that the exact quantities of substances needed for a specific output are known. The observation period is generally over multiple years, and at different levels (national, regional, company level) (Brunner et al. 2003).

Life cycle assessment (LCA) describes the inputs and outputs of a system with environmental relevance (DIN EN ISO 14040). The gate-to-gate LCA describes the activities within the walls of the factory. LCA generally balances each step in the manufacturing process and translates the system outputs into a $CO_2$ footprint using a database reference values.

Input-Output Methods can transparently depict a single state or multiple state over time through multiple measurements. They however require expert knowledge to identify which inputs are relevant and interpret cause- and effect relationships, for instance in a case where two input parameters vary, seemingly causing a jump in an output value. Therefore the causal relationships between activities and material waste is not identifiable. The granularity of the analysis flexible. This means one company may treat an entire plant as a black box, only examining input parameters and the resulting outputs of the factory as a whole, while a neighbor plant may perform a balance of each workstation.

### 4.1.2 Material Flow Cost Accounting (MFCA)

Material flow cost accounting presents an instrument to quantitatively analyze material consumption or utilization in processes and evaluate these monetarily. Building on the principle of inputs-output analysis, MFCA conducts a balance of each process or sub-process, called a quantity center (ISO 14051 2001, pp. 31). Both value adding and non-value adding processes (e.g. handling, storage) can be analyzed. For each quantity center measurements of all material and energy inputs are taken, as well as all product, waste material, or energy outputs. The material flows can then by traced by connecting the outputs of an upstream process to the inputs of its downstream counterpart. The flows of material towards a finished product are clearly differentiated from material waste flows. In a second step, material costs, energy costs, and system costs are allocated to the quantity centers.

MFCA provides more structure than its more general input-output analysis counterparts. It transparently demonstrates the amount of material waste and costs associated with material waste in the process chain, identifying the most costly and most material intensive processes. However the processes are broadly defined (e.g. receiving, milling), providing no insight into the better operation of a single process or process chain through the tuning of scheduling parameters e.g. a lot-size optimization.

### 4.1.3 Ecological Value Stream Mapping (VSM)

Erlach's $CO_2$ Value Stream Analysis is an expanded form of the classic value stream analysis, a static method for modelling the performance of a production system. The value stream analysis begins with a collection of process data such as operation times, lot sizes, process availability, change over times, and shift schedules. The method calculates and compares the process cycle time (capacity) and customer tact time (demand) in a balancing diagram to identify bottlenecks and overcapacities and measures the agility of the system by calculating the throughput time of the. In the ecological counterpart to this method, energy and material consumption are measured per process and per workpiece. Erlach breaks down the energy consumption into standby-and active processing portions. Ecological metrics, like a carbon footprint, may also be calculated using a LCA software (Erlach et al. 2012). Kasava et al. and Faulkner et al. present similar approaches (Faulkner et al. 2014) (Kasava et al. 2015).

Unlike the input-output method, the value stream method provides some detail into the throughput of the manufacturing process while still balancing the inputs and outputs. For instance, a CO2 value stream map depicts the amount of time in which the process produces good workpieces and waste (e.g. defects). However, details describing the consumption of material during other activities, e.g. setups are ignored. Additionally the approach extracts little information on the cause of material waste or its influence parameters.

### 4.1.4 Comparison of Analysis Methods

This section evaluates the analysis methods on their ability to fulfill the solution requirements defined in 3.1 and 3.2.

To reach the goal of estimating savings potential of material efficiency activities (R1) it is important that the initial data collection surveys material consumption data, cost data, and performance data under as many different system conditions as possible. Similarly, R2 requires data on a number of other output parameters, including cost and serviceability, to ensure goal conflicts are identified and addressed. A pure material input-output analysis and material flow analysis would not collect the cost information and performance information. When performing a gate-to gate LCA, data on cost and ecological consequences is collected only for a reference case, therefore LCA receives only a partial score. MFCA collects and demonstrates waste costs by process, therefore a user may be able to estimate cost savings by comparing the conditions in different consideration periods. However, no data on the non-monetary performance of the system is collected in MFCA. While Erlach's value stream analysis does not evaluate process costs, some adaptations do. Value stream analysis is the only considered method that measures non-monetary system performance (e.g. throughput times), however only statically.

**Table 5: Evaluation of analysis methods**

| Body of Work | Method | R1.Savings potential | R2. Goal conflicts | R3. Fast and low effort | R4. Fluctuating product spectrums | R5. Process chains and relationships | R6. Multiple materials | R7. Dynamic behavior | R8. All material consuming activities | R9. Causality modelling |
|---|---|---|---|---|---|---|---|---|---|---|
| Binding 1988<br>Slawik 2012 | Input-Output Analysis | ○ | ○ | ◔ | ◐ | ◔ | ● | ○ | ● | ◔ |
| Ghadimi et al.<br>Wohlgemuth et al.<br>Brunner et al. | Material Flow Analysis (MFA) | ○ | ○ | ◔ | ◐ | ◔ | ● | ○ | ● | ◔ |
| DIN EN ISO 14040 | Gate to Gate Life Cycle Assessment (LCA) | ◐ | ◔ | ◐ | ◐ | ◔ | ● | ○ | ● | ◔ |
| DIN EN ISO 14051 | Material Flow Cost Accounting (MFCA) | ● | ◔ | ◐ | ◐ | ◔ | ● | ○ | ● | ◔ |
| Erlach et al.,<br>Faulker et al.,<br>Kawasa et al | Value Stream Mapping (VSM) | ◔ | ◐ | ◕ | ◐ | ◐ | ● | ◔ | ◕ | ◐ |

| ○: lowest degree of fulfilment | ◔: low degree of fulfilment | ◐: moderate degree of fulfilment | ◕: high degree of fulfilment | ●: highest degree of fulfilment |
|---|---|---|---|---|

In terms of effort (R3), Input-Output Analysis and MFA require the measurement of defined inputs and outputs over a longer period of time, which can generally be automated and then reviewed for analysis. Using an LCA software to calculate a carbon footprint metric generally make LCA somewhat more time-intensive than an Input-Output Analysis. The tracking and allocation of material and cost data makes MFCA also moderate in effort. Value stream analysis is considered the highest effort of these methods as performance data is also collected for each process.

For adaptation to fluctuating product spectrums (R4) a data collection method must be either product-family overarching or easily repeatable. Since the latter point is already addressed in R3, the evaluation focuses on the former point. Assuming the process chain is identical for multiple products and all products are lumped together, product-specific outputs are not traceable to their cause in any of these methods I-O Analysis, MFA, LCA, MFCA, and VSM. Therefore all methods are rated equally poorly.

R5 seeks to improve material efficiency by understanding the interdependencies between logistically linked processes or those in close physical proximity. To the former point, the supplier and customer relationships are clear in each method, yet how large the material buffers between the processes must be to bridge short disruptions is only visible with VSM (e.g. ConWIP formula) (Erlach 2013). To the latter point, the physical proximity of the processes in not considered in any of the abovementioned methods.

VSM may provide collect some of the necessary data for a dynamic production simulation, however only mean values, e.g. the mean-time-to-repair rather than a distribution of repair times. In contrast the other methods provide little to no information on the dynamics of the production system (R7).

All of the abovementioned methods can collect data on multiple material flows (R6), though through the focus on core value-adding processes VSM often ignores material waste from peripheral processes (R8).
Of all of the examined methods, VSM collects the most information on causality (R9), in that the user is forced to break material consumption down into different states (e.g. processing and standby) on a machine, though many activities and their causal relationships are not considered. Due to the black-box perspective, the other methods are comparable to one another.

## 4.2 Synthesis Methods

The synthesis method should provide users with an established and comprehensive basis for making material efficiency decisions at the factory level.
In this section, methods described in recent scientific publications, which strive to solve similar research problems utilizing simulation-based approaches are examined, to identify to what extent they fulfill the requirements of the solution (established in 3.1 and 32). Although the system dynamics paradigm is better suited for modelling material efficiency, simulation-based methods pursuing material efficiency using a discrete event, system dynamics, or hybrid paradigms are described.
Among the many works examining material waste flow simulation, the degree of detail with which material waste is simulated varies greatly, from rough lump sums per product produced, to more detailed material waste rates in machine operating states. The former category is described in the first section, while the latter is described in the second.

### 4.2.1 Lump Material Waste Quantity Simulation

Wohlgemuth et al. (Wohlgemuth et al. 2006) combines material flow analysis (Umberto Software) with discrete event simulation (Microsoft COM-based).

Material waste is the output of transition events, where input materials are converted to products and waste depending on "production coefficients". A conventional DES simulates a sequence of transition events.
Junge simulates the consumption of material as an emission in a coupled material and thermal manufacturing system simulation. An emissions parameter is entered for each product and process, but not broken down by causality (Junge 2007).

Löfgren simulates the LCA impact of a product under varying conditions. Energy consumption, trim loss, chips, defects, and even machine wear are attributed as a lump amount to each product (Löfgren 2009).

Greinacher (Greinacher et al. 2015) describes a simulation-based method to model material efficiency. Similarly, to Junge and Löfgen, the amount of material waste is assumed constant per process.

#### 4.2.2 State-based Material Waste Quantity Simulation

Heilala et al. (Heilala et al. 2008, pp. 1928) presents the SIMTIR framework, which uses an operating state based discrete simulation to predict energy and resource consumption. Multiple material waste flows are calculated, yet it is unclear if the material waste is allocated to the energy-relevant operating states: idle, down, busy, repair (Heilala et al. 2008, pp. 1928).

Duflou et al. (Duflou et al. 2012, pp. 590) presents an inventorization method to allocate material waste, operating materials consumption, and power consumption to process specific "production modes". Each production mode represents a single activity or operating state observed on a machine of specific technology, e.g. Sintering production modes: process exposure,

preheating, cooling, recoating, cooling down, and cleaning. Based on the production mode measurements a DES Simulation can be performed.
While this method has its merits in increasing the degree of detail of material waste flows to that of power consumption, it fails to address the differences between material waste and energy consumption by adopting production modes based solely on the power consumption behavior. Secondly, the relationship between the production modes is unclear, e.g. which conditions trigger each production mode? A technology-specific approach can be cumbersome for manufacturers, as it requires a long analysis of machine data, video material, or employee protocols to identify distinct production modes and to allot the material consumption to each one.

Alvandi et al. (Alvandi et al. 2015) simulates material and energy flows at the multi-machine level of manufacturing systems, although the focus is on operating materials. The work builds on the premise that there is a characteristic material consumption or a material consumption profile for a manufacturing process in a specific machine operating mode. The approach borrows the operating mode definitions from the energy consumption modelling approaches of Haag, Dietmaier et al., Verl et al. (Dietmair et al. 2008; Dietmair et al. 2008; Verl et al. 2011; Haag 2013). The method assumes the mode-specific material waste profiles are static, ignoring the effect of time-dependent factors (e.g. exhaustion) or external disturbance factors (e.g. temperatures). However, the significance of mode transitions is acknowledged.

Sheehan et al. (Sheehan et al. 2016) builds on the premise of operating-mode based modelling, extending the definition of machine operating modes to describe inventory stockpiles. Analogous to a characteristic energy profile, a characteristic material waste profile is allocated to each operating mode.

However, since operating mode transitions are particularly turbulent for machine stability, a lump material loss is assumed for each operating state transition, independent from the material waste profiles. This effect is ignored in the analogous energy efficiency work, because the increased energy consumption is negligible (Haag 2013). Individual material waste profiles are determined for each waste form and each mode or intermodal transition via measurement. Sheehan et al. mentions that Haag's energy-relevant operating states: work, warmup, wait, block, error, setup, off/standby, and save, are not relevant to material efficiency in their entirety, though certain modes, like setup, have a different type and quantity of material consumption. A set operating mode chart determines which transitions are possible under which conditions.

Hopf (Hopf 2016, pp. 81) presents an operating state oriented modelling method for both energy and material resources in production systems. The machine finds itself in one of three main operating states at all times: operation, no operation (off), and standby. While transitions between main operating states are infrequent, perhaps only once a day, the machine frequently switches between sub-states in the main operation state. These consist of work-ready (waiting), operation-ready (idle), work (and process specific work variations), preparation, error, startup and shutdown.
Hopf's approach distinguishes between the short-interval operating states and the long interval states, an obvious but important observation in the understanding of machine dynamics, which has been neglected in other works. However the reasoning for the differentiation, e.g. to the required planning for an early a machine-shut-off vs. machine idling is not specifically presented. Like the other works, a generic structure for operating state logic, or a set of conditions, under which an operating state is maintained or changed, is missing. Similarly, to the other approaches, the multitude of operating states

is solely justified through load profiles, not a distinct material consumption or waste occurrence patterns.

**Table 6: Operating state structure and origin in material efficiency simulations**

| Body of work | Operating states | Transitions | Origin of states | State logic |
|---|---|---|---|---|
| ***Heilala et al. 2008*** | idle, down, busy, repair | Not stated | Not stated | Not stated |
| ***Duflou et al. 2012*** | Process-specific, e.g. exposure, preheating, cooling, recoating, cooling down, and cleaning | Included as state | Process observation | Not stated |
| ***Alvandi et al. 2015*** | Pre-production, production, post-production, ramp-up, failure, off, change-over, ramp-up, pre-production, | Modelled / Included as State | Observation metalworking process | Petri-net based, conditions not states |
| ***Sheehan et al. 2016*** | Off, work, error, idle, setup | Modelled separately with lump material quantity (e.g. startup losses) | Eliminating non-material relevant operating states from Haag (machine control) | State-diagram with conditions |
| ***Hopf 2016*** | No operation: standby; operation: work-ready (waiting), operational (idle), work (+ process specific work variations), preparation, error, startup and shutdown | Included as state | Energy consumption profiles | Possible transitions highlighted, no conditions |

In Table 6, the differences between the machine operating state-oriented simulation approaches are summarized. Comparing the selected operating states and their justifications, four commonalities between the methods arise which are described in detail below.

1. **Considerable number of operating states**: significant variation in material waste compositions or quantities under different conditions warrants the definition of a separate operating state. If the measured waste quantities are nearly identical, the additional measurement effort must be weighed against the benefit of multiple operating states. Practical application of the methods requires measurement of each material waste- machine-operating state-

product variant combination. If additional lump material waste sums occur when transitioning between operating states (e.g. starting up, or suddenly idling), the number of measurements quickly escalates.

2. **Tailor-fit to energy modelling**: due to the current trend to model material consumption as a small aspect of resource consumption, approaches tailor-fit to energy consumption are transferred to material consumption with minimal adaptation. The selection of operating states has been chosen based on their characteristic energy loads, not material consumption. Multiple operating states may be identical with respect to material efficiency, while characteristically different operating states for material may have been ignored or lumped with others.

One of the most common and expensive material waste forms, startup losses after setups, cannot be allocated to any of the described operating states and requires the modelling of transitions between operating states, which is often neglected in energy efficiency modelling (Haag 2013, pp. 74).

3. **Operating states vary, are technology specific, or experience-based**: both different terminology as well as varying definitions are used to describe operating states, making it unclear which set is the most accurate and concise. Some sets are clearly only accurate for a single technology, such as those presented in Duflou et al., while other are seemingly generic but based on experiences with machine controls on certain types of technologies.

4. **Unclear operating-state-logic**: while some author's provide a state-diagram of the possible transitions and the conditions to make a state-transition, there is no consensus on a generic operating state logic. A generic state logic is necessary for practitioners to have a starting point for modelling their production system, if the real conditions for state- transitions are unknown or too complex for the simulation.

### 4.2.3 Comparison of Synthesis Methods

The dynamic modelling approaches have the potential to capture the dynamics of waste streams, though the work of Alvandi et al. uses the operating mode logic of a single machining process, begging the question of their universal applicability without individually identifying operating states and a reasonable transition logic for each possible machining process individually. Sheehan et al. uses a generic set of operating modes, but a fixed operating mode logic. Additionally the material waste profiles in each operating state in each process are measured values, making data collection too cumbersome for most companies. The deficits of these methods are summarized in Table 7.

With respect to estimating savings potential and highlighting goal conflicts, it is important that not only the accumulated material waste is modelled, but also the performance of the manufacturing system. The process-based systems model the material waste as a lump sum per part and process, therefore the savings potential of improvement measures may not be seen, unless it results in producing fewer orders. To that point, goal-conflicts, lowered material efficiency through more startup losses when reducing lot sizes would also go unseen. Therefore in R1 and R2 all of the process-based methods received poor ratings. Each of the operating-state based approaches estimates both savings potential and addresses goal conflicts more clearly. However many of the methods only model material waste in direction connection with a fabrication machine: any shrinkage in storage downstream is ignored. Therefore a goal-conflict, large lot sizes for less start up-losses vs. inventory shrinkage through high inventory levels, would be ignored. Each of the methods, with the exception of Sheehan et al., ignore inventory deterioration.

**Table 7: Evaluation of synthesis methods**

| | Body of work | R1.Savings potential | R2. Goal conflicts | R3. Fast and low effort | R4. Fluctuating product spectrums | R5. Process chains and relationships | R6. Multiple materials | R7. Dynamic behavior | R8. All material consuming activities | R9. Causality modelling |
|---|---|---|---|---|---|---|---|---|---|---|
| *Process-based* | Wohlgemuth et al. 2006<br>Junge 2007<br>Löfgren 2009<br>Greinacher et al. 2015 | ◔ | ◔ | ◕ | ◐ | ◔ | ◐ | ◔ | ◔ | ◔ |
| *Operating – state- based* | Heilala et al. 2008 | ◐ | ◐ | ◔ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |
| | Duflou et al. 2012 | ◐ | ◐ | ○ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |
| | Alvandi et al. 2015 | ◐ | ◐ | ◔ | ◔ | ◐ | ◔ | ◐ | ◐ | ◔ |
| | Sheehan et al. 2016 | ◐ | ◕ | ◔ | ◔ | ◐ | ◕ | ◐ | ◕ | ◔ |
| | Hopf 2016 | ◐ | ◐ | ◔ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |

○: lowest degree of fulfilment ◔: low degree of fulfilment ◐: moderate degree of fulfilment ◕: high degree of fulfilment ●: highest degree of fulfilment

In terms of effort (R3), each of the process-based methods has a clear advantage. If average historical waste quantities can be allotted to a single piece, waste measurement may not be necessary. As mentioned, operating-state methods require a measurement per machine-material-waste-operating state-product variant combination, as well as for transitions, considerable effort. In Duflou's approach, the set of operating state varies by technology, requiring in-depth process analysis of each technology and the abovementioned measurements.

None of the methods presents an approach to estimate the future material consumption of a product before serial production, creating a delay between start-of production and application of the method. The delay leaves manufacturers of products with ever-shorter lifecycles little time to take action before the next product generation arrives (R4). Of all the methods, the process-based lump sums is the fastest, if snapshot measurements are used instead of averages.

While all of the methods model the logistical relationships between supplier and customer processes in a simulation (R5), few of methods describe more explicitly which conditions in the relationships trigger a change in machine operating state (operating state logic). Therefore each of the methods that describes the operating states is rated as moderately fulfilling the requirement. The spatial relationships between processes and the resulting effects (e.g. contamination) are not addressed by any of the methods.

Multiple materials (R6) are addressed in most of the works as a component of resource efficiency, although specific waste types are rarely described. Junge describes the consumption of utility-similar consumables, ignoring raw material wastes (Junge 2007). Alvandi et al. models only cooling fluid consumption in a metalworking process, though process defects and chips surely also occur (Alvandi et al. 2015). Sheehan et al. mentions specific waste forms, including plastic granulate, half-finished workpieces, paint, and filter materials (Sheehan et al. 2016).

Dynamic behavior (R7) of the system with respect to logistical performance is modelled, though the material consumption is static. In the process-based methods it is equal to the product of a lump sum per piece and the production volume, while in the operating state based methods the product of time in an operating state x the typical material waste rate are taken. Changes to the material waste rates under different conditions are acknowledged by Sheehan, but not detailed (Sheehan et al. 2016). The effect of material waste accumulation affecting the performance of the system, e.g. more machine idling due to employee absence for waste disposal, or increasing waste rates in neighboring areas due to cross-contamination, is not featured.

In addressing all material-consuming activities (R8), most authors draw the line at the limits of the machine-system. This is especially the case for operating-state based methods, since the material consumption is linked to a specific machine operating state. Activities that occur independently from the machines operating state (e.g. cleaning) are not recorded. Similarly, inventory shrinkage, often not in the proximity of manufacturing machines, is completely ignored in most cases, though Sheehan et al. does suggest modelling stockpiles also as operating-state-dependent work centers.

Holistic causality modeling (R9) addresses a number of possible influence parameters, for instance the machine, man, material, method, and environment. The machine focus of all of the investigated methods conceals the influence of the employee in material consuming activities. The above mention methods model neither changes in material characteristics outside the intended transformation process nor changing ambient conditions around the transformation process. Therefore each of the methods receives a low score.

## 4.3 Specifications for the Developed Solution

Reviewing the common deficits of the analysis and synthesis methods (see Table 5 and Table 7), solution specifications are formulated in Table 8.

Overall, the current analysis methods capture a high level or static view of the production, with few exceptions. At this level and with this limited scope, cost and performance information are also ignored in many examples. The most thorough of the methods utilize static measurements in different operating states and determine the conditions for state changes empirically.

**Table 8: Solution specifications**

| Deficits in state of research | Specifications for solution |
|---|---|
| **Analysis methods**: | |
| Cost and performance data ignored (R1/R2) | The solution collects material waste parameters as well as cost and performance parameters. |
| Data collection oversimplifies dynamics of production system (R7) | The solution considers dynamic product mixes and volumes and dynamic effects |
| Data collection is performed at a high level where interdependencies are invisible (R7/R9) | The solution collects data at the multi-machine level, considering the material waste quantities connected to operating states and activities. |
| **Synthesis methods:** | |
| Simulated operating states are irrelevant/incomplete for material waste modelling (R3/R6/R7/R8) | Identifies the operating states relevant to material and aligns them with the existing energy consumption operating states |
| Non-mechanized supporting activities neglected (R8) | Operating-state independent activities and processes integrated in the model |
| Holistic causality not addressed (R9) | The influence of man, materials, method and environment on the operating state specific material consumption values is included |
| Production dynamics dictate material consumption without feedback (R5/R7/R9) | Account for the case of material waste consumption effecting the dynamics of the production system |

The strongest synthesis methods utilized operating state modelling, whose merits lie in connecting the consumption of resources with the dynamics of the production system.

The operating state paradigm provides a compromise between overly simple lump sum per piece calculations and detailed simulation of every process sub step.

However certain deficits of the existing operating-state-based simulation methods must be remedied in the solution. The chosen operating states are tailor-fit to energy consumption, resulting in superfluous material waste measurements or neglecting material consuming operating states.

The machine focus of the operating state orientation presents a challenge for holistic causality for two reasons: a) non-mechanized supporting activities, including handling and goods storage are ignored and b) the role of other influence factors (man, material, and environment) is unclear.

Currently this connection between the dynamics of the production simulation and resource consumption is unidirectional: the production schedule dictates the operating states, resulting in resource consumption. The reality paints a different picture: the production schedule are adjusted to account for lost employee time, cross-contamination issues, and prevent undesirable product sequences that cause excessive material waste (e.g. frequent paint-shop color changes).

## 5 Causation of Material Waste in Manufacturing

Based on the lack consideration for holistic causality in the existing operating-state-based simulation approaches (see Section 4), this section investigates the causal relationships between influence factors in the factory system and the occurrence of material waste. After examining the effects of man, machine, material, method, and environment a list of influence factors is consolidated. From this list of influence factors, a set of material waste causing activities and events in the factory are identified and compared with the activities already modelled in operating-state-based production simulation.

In a second step, the author examines which influence factors and activities can be influenced by OM, and which exceed its authority.

### 5.1 Ishikawa Analysis

In this section Ishikawa diagrams, or cause-and-effect diagrams, provide a classification structure for the numerous causes and influence factors for the occurrence of material waste. Influence parameters identified in experimental studies, research publications, as well as practical literature are classified into five categories by their origin: machine-induced, material-induced, employee-induced, ambient-condition induced, and method-induced. The term machine-induced refers to machine parameters and machine conditions e.g. with respect to wear. Material-induced refers to both the specifications of the ingoing material and the product specifications. Employee-induced describes waste caused or influenced by the machine operator or material handlers in direct contact with the material, and excludes the decisions of managers. Ambient condition-induced characterizes material waste caused directly by conditions the shop floor. Method-induced refers to waste caused by policies and decisions of managers, production schedulers, and maintenance planners.

Since materials serve a number of purposes in the factory and are damaged or discarded for different reasons, individual Ishikawa diagrams provide more insight into the causality than one large diagram. Eleven material waste forms are selected, as depicted in Figure 22, which are typical for parceled goods manufacturers. The considered waste forms include both materials in the main (raw, auxiliary) and operating material flows. In line with Erlach et al., lost workpieces are classified by their occurrence location, either in processing, in warehousing, or in transport, and designated as “process defects”, “inventory shrinkage”, or “transport loss” respectively (Erlach et al. 2014, pp. 657). Subtractive losses, which are different from the desired product in form or chemical composition, are clustered by their typical designation in technical literature: “trim loss” for the remaining material after cutting processes, “chips” which describe the small material mass removed during machining operations, and “byproducts” which describe remaining raw material that is separated due to its undesired chemical composition. Section 5.1.7 describes coatings and joining materials, as examples of typical auxiliary materials found in the piece goods industry. Rather than material damage or contamination after a single use, material drag-out and aging affect closed-loop operating material (CLOM) systems. Therefore Section 5.1.8 describes the causation of material waste in closed-loop systems, where the material comes in contact with the workpiece, while Section 5.1.9 describes the causation of closed-loop operating materials without direct contact with workpieces.

Section 5.1.10 and Section 5.1.11 describe single-use operating materials, namely cleaning products (5.1.10) and packaging and protectors (5.1.11).

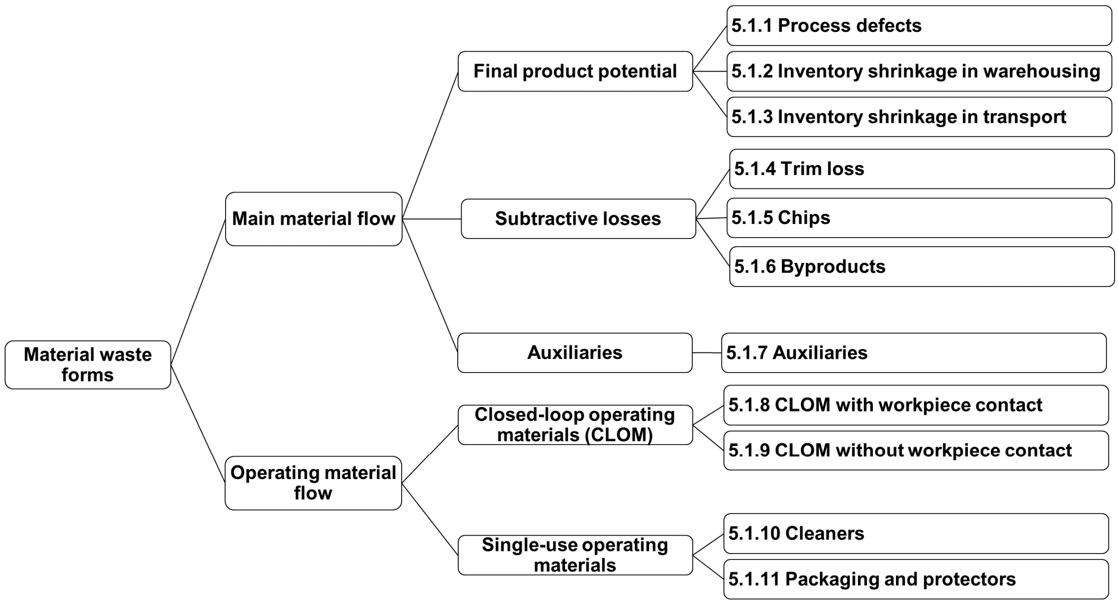



**Figure 22: Selected forms of material waste discussed in Section 2**

### 5.1.1 Process Defects

Process rejects, scrap, or defects refer to material damaged or lost in a manufacturing process intended transform it into a full-value product or a major component of the product.

#### 5.1.1.1 Machine-Induced Process Defects

**Poor conception of the production system (work station arrangement, speeds, automation degree):** Cheng et al. found that certain machine and assembly concepts yield fewer defects due to shorter handling distances, fewer hand-overs, and enabling employee communication (Cheng et al. 2000, pp. 324). Khouja and Mehrez find that high speeds impede quality in both manual and automated work content (Khouja et al. 1995, pp. 345; Mehrez et al. 1996, pp. 224; Khouja 1999, pp. 4075). Increased automation is shown to lessen defect rates on the example of welding (Inman et al. 2003, pp. 1964).

**Worn machine, components, or tooling:** Santos modelled machine-error-induced defects as a "bathtub curve" with respect to machine and tool age (see Figure 23), where machine-errors occur more frequently in Zone I, the infant period, and Zone III, the waste-period. Zone II, known as the useful period, can be lengthened though maintenance and repair (Santos et al. 2006, pp. 116).

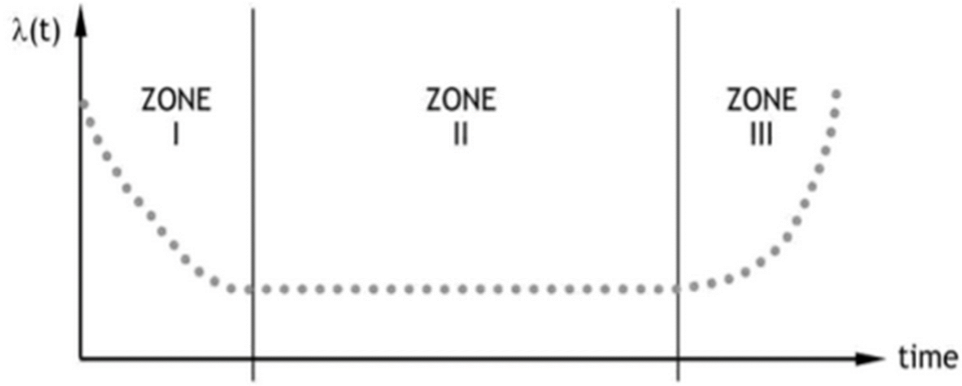



**Figure 23: Frequency of component failure over time (Santos et al. 2006, pp. 116)**

Similarly, Filipovic found that cutting-fluid systems experience degradation with exhaustive use and skipped maintenance activities (Filipovic 1998, pp. 390).

5.1.1.2 Employee-Induced Process Defects

**Operator stress levels:** Scholars like Govindaraju found correlations between defect rates in manual assembly operations and employee stress levels, which can be heightened by physical, psychological, sensory, and mental conditions (Garvin 1988, pp. 152; Govindaraju et al. 2001, pp. 362).

Lin et al. and Wick et al. linked stress due to unergonomic postures with lowered yield in camera assembly lines (Wick et al. 1998, pp. 39; Lin et al. 2001, pp. 380).

Eklund describes "psychologically demanding tasks" as leading to higher defect rates, supporting Mehrez's thesis that increasing automation improves quality (Eklund 1999, pp. 156). Matanachai describes very high workload levels as a cause of employee stress, with negative effects on product quality (Matanachai 2001, pp. 30). Khouja found rebalancing assembly lines to increase output has been linked with increased employee stress and higher defect rates (Khouja 1999, pp. 4075).

Garvin linked the use of overtime with lower quality rates, possibly due to increased emotional stress of balancing work and private life as well as relocating labor across production networks (Garvin 1988, pp. 152).

**Operator confusion:** Cheng establishes that number of components in an assembly operation increases the likelihood of quality defects, as the room for human error is larger (Cheng et al. 2000, pp. 323). Similarly, Inman asserts the lack of modularity in a product design decreases product yield (Inman et al. 2003, pp. 1964). One driver of confusion is clearly the product variety performed by the same operator within a period and small lot sizes.

Another driver is the similarity between different product variants, which leads to mismatched parts or steps: these include similar precedence diagrams, frequent product updates, and overlapping product life cycles (Garvin 1988, pp. 153; Inman et al. 2003, pp. 1964).

**Lack of group problem solving:** Cheng describes too little communication between operators as a quality-hindering factor, which is rooted in work center design (Garvin 1988, pp. 149; Cheng et al. 2000, pp. 327).

**Lack of operator motivation:** Employee motivation may play a role in product quality due to apathy, or in more extreme cases negligence and sabotage (Piątkowskia et al. 2015, pp. 63).

**Operator not adequately qualified:** Without the necessary qualifications, the employee lacks knowledge of quality failure types and problem solving skills, or may pose a safety risk (Dal et al. 2000, pp. 1497; Averill 2011, pp. 47).

#### 5.1.1.3 Ambient Condition-Induced Process Defects

Ambient conditions generally affect product quality indirectly by causing changes in machine parameters, material characteristics, or employee performance, as shown in Figure 24.

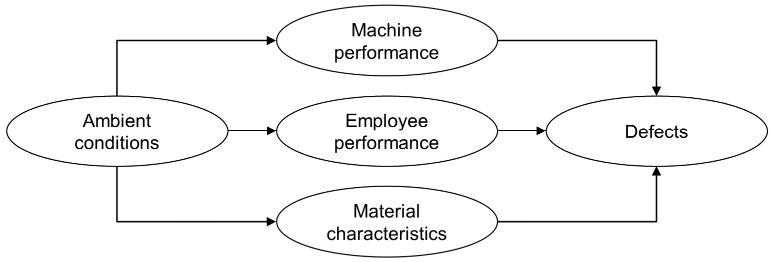



**Figure 24: Relation of ambient conditions to product quality**

**Air quality:** multiple studies demonstrate the effect of air contamination, temperature, and changes in air pressure in the direct vicinity of a production process or in storage areas on product quality (Dal et al. 2000, pp. 1497; Li et al. 2007b, pp. 2). Variable humidity causes defects when processing hygroscopic materials (Henry 2013, pp. 6). For some sensitive processes, process defects may cause changes ambient conditions locally, potentially further increasing the quantity of defects.

**Vibrations and noise:** Machine vibrations, stemming from the processing machine or neighboring machines, may increase process parameter variance and therefore defect rates in sensitive processes (Li et al. 2007a). Employee performance is contingent on noise levels in the factory (Realyvasquez et al. 2016, pp. 104).

**Lighting**: Poor lighting conditions (too dim) increase defect rates in both fabrication (metalworking) and a number of manual assembly processes as well as decreased employee productivity (Völker 1999; van Bommel et al. 2002, pp. 52).

#### 5.1.1.4 Material-Induced Process Defects

**Material out-of-spec or incorrect material:** Failure to catch defects in upstream processes or out-of-spec materials in goods receiving, as well as feeding incorrect material into a machine not only wastes machine capacity but may destabilize machine parameters or cause cross-contamination.

**Material spreads contamination:** Similar to the effect of air contamination, workpieces themselves can serve as a medium for contamination (Li et al. 2007b, pp. 2).

Changes to the operating materials within the system, such as undesired changes to the composition of cutting fluid over time (e.g., too low pH, too low or too high oil concentration) can affect product quality (Filipovic 1998, pp. 389–390).

#### 5.1.1.5 Method-Dependent Process Defects

**Lack of quality planning and control:** Garvin found that skipping pilot runs, led to higher defect rates in series production. Utilization of failure modes and effects analysis (FMEA) and reliability engineering techniques are also identified as success factors (Garvin 1988, pp. 136).

Lundal and Juran claim that increased quality control forces companies to confront problems and therefore leads to lowered defect rates (Fine 1986, pp. 1301).

**Lack of segmentation:** High product variety in a production line is correlated with to higher defect rates in multiple studies, though Garvin found that the number of product architectures is more predicative of the defect rate than the number of models (Garvin 1988, pp. 139; Inman et al. 2003, pp. 1962–1963).

**Poor machine-product variant match:** if a facility has multiple production resources, differences in quality may be observed from machine-to machine to the same product variant.

**Unfavorable processing sequences:** If product variants are sequenced from "weak to strong", starting with the product varieties most sensitive to contamination and working up to the most robust, the defect rates of the sensitive products are lessened, e.g. running light to dark colors in a paint shop (Henry 2013, pp. 53). Unfavorable production sequences present a source of variance, due to employee mix-ups (Garvin 1988, pp. 149; Inman et al. 2003, pp. 1964).

**Lot sizes are too large or too small:** Machine instability preceding or following a machine setup may cause increased defect rates, known as "startup loss" and "shutdown losses" (Reitz 2008, pp. 65). In some setup procedures, raw material is used to test adjusted machine parameters, and these pieces are discarded (Henry 2013, pp. 9). Therefore the more frequent setups occur, the higher the defect rates. Aside from the immediate startup losses some scholars model yield rates as increasing over a production run due to a learning curve and fine-tuning (Garvin 1988, pp. 151–154; Gallego et al. 1993, pp. 1499; Bourland et al. 1997, pp. 417).

However other scholars argue unrecognized process destabilization occurs over the course of a run, therefore smaller lot sizes lessen the time in an instable state (Porteus 1986; Rosenblatt 1986, pp. 48; Urban 1998, pp. 3093; Khouja 1999, pp. 4068). Chand argues that small lot sizes train employees to more efficiently run the process, lessening startup losses per run and setup material consumption through routine (Chand 1989, pp. 197). Inman suggests small lot sizes force the operator to intensively monitor each machine and immediately react to errors (Inman et al. 2003, pp. 1963).

**Irregular loading:** Varying monthly production loads may increase defect rates (Garvin 1988, pp. 150). Longer periods of machine inactivity may cause increased startup losses (Manzini 2010, pp. 74).

**Too few maintenance activities:** Too little or too infrequent planned maintenance activities increase defect rates (Santos et al. 2006, pp. 118; Selaouti et al. 2010, pp. 6).

5.1.1.6 Defect Causation

To some extent, quality defects are predetermined for a machine or assembly center by design, as shown in Figure 25. However, the current conditions on the machine are subject to time and load-based wear, which also have an effect on defect rates. Within this work, the design of production systems is assumed given for any existing production system and therefore any changes to the design of the production system will not be considered as a tactical or operational improvement measure to increase material efficiency.

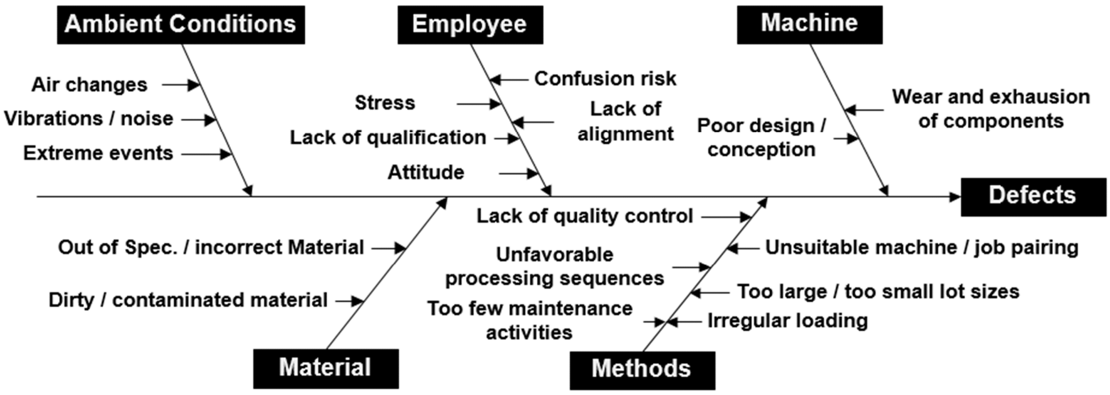



**Figure 25: Causation of process defects**

## 5.1.2 Inventory Shrinkage or Deterioration

Inventory shrinkage is defined as the monetary loss of material inventory for any reason, including theft. However, in this thesis, inventory shrinkage will be used to describe a loss in material value, and therefore theft is excluded. Inventory deterioration more specifically refers to the loss in material value due to decay, evaporation, damage, or technological obsolescence (see Figure 26).

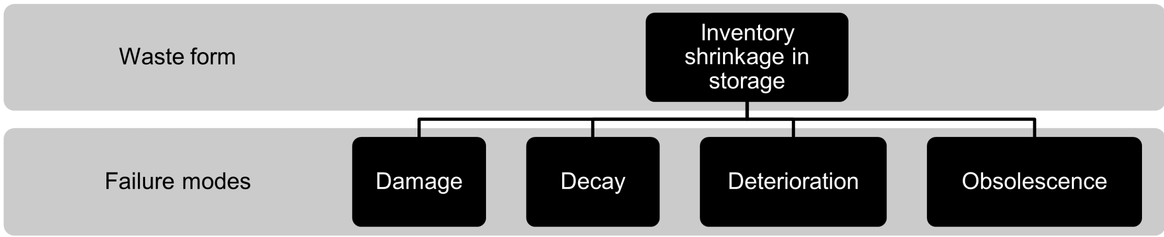



**Figure 26: Failure modes of inventory deterioration in storage**

### 5.1.2.1 Employee-Induced Inventory Deterioration

**Employee lacks motivation:** Physical damage due to over-stacking materials, using the incorrect packaging, or putting too much load on certain products can be linked to employee faults due to low motivation (Bragg 2011, pp. 77). Negligence in warehousing may lead to misplaced products and extended holding periods, and therefore a higher risk of product decay or technical obsolescence (Huber et al. 2007, pp. 2).

### 5.1.2.2 Material-Induced Inventory Deterioration

**Material is not shelf-stable:** Some materials perish or lose chemical stability (fresh foods, film) over time, and therefore have a shelf-life (Goyal 2001, pp. 2; Dris et al. 2004, pp. 231; Ho et al. 2007, pp. 2564). A high modulus of elasticity and high water content can also cause changes in product composition and loss of value (Ytterberg 1992, pp. 1–2) (Entrup 2005, pp. 105).

**Material is subject to obsolescence:** Fashion goods, and other products with frequent technical or aesthetic updates are vulnerable to obsolescence and an immediate drop in value (Goyal 2001, pp. 2).

### 5.1.2.3 Ambient Condition-Induced Inventory Deterioration

**Ambient conditions out of range:** Air circulation, temperature, sun exposure, humidity, and exposure to pests can affect material wastage depending on the product (Ytterberg 1992, pp. 1–2; Wood et al. 1995, pp. 333; Venkateswarlu 2001, pp. 166; Hui 2004, pp. 204; Vajna 2014, pp. 234).

**Extreme conditions:** Fire and flooding lead to material loss (Tompkins 1988).

5.1.2.4 Method-dependent Inventory Deterioration

**Inadequate storage infrastructure:** Inappropriate packaging method may shorten shelf life (Tompkins 1988, pp. 846). Inadequate storage beds and surfaces may also be to blame (Ytterberg 1992, pp. 2). Stacking goods too high due to lack of storage space may lead to shrinkage (Bragg 2011, pp. 77).
**Inventory level is too high / holding time is too long:** Inventory deterioration rates are modelled as a function of inventory holding time, often due to over-anticipating demand (poor forecasting) or over-ordering bulk raw materials for discounts (Taub et al. 1998, pp. 377). Minimum lot sizes may increase the holding time for slow-movers (Zhou 2013, pp. 1984).
**Unfitting dispatch policy:** Permitting payment after shipping leads to shorter holding periods for finished products in the factory (Goyal 2001, pp. 3) .
Selecting product dispatch policy (e.g. FIFO, LIFO, expiration date) based on product decay behavior can reduce inventory deterioration rates for make-to-stock products (Taub et al. 1998, pp. 377).
**Conservative shelf-life policy:** While product shelf-life is fixed by law for some products, others are company internal specifications (Goyal 2001, pp. 3). Too strict internal specifications may lead to unnecessary product disposal (Entrup 2005, pp. 105).

### 5.1.2.5 Summary of Inventory Deterioration Causation

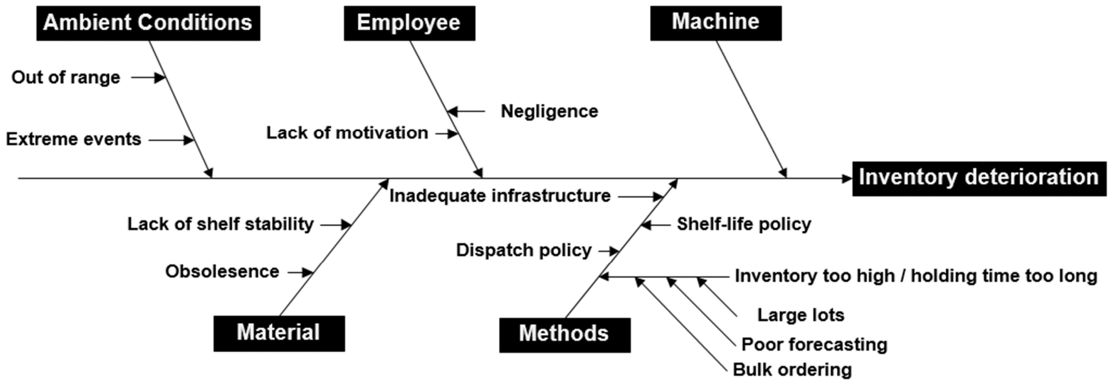



**Figure 27: Causation of inventory deterioration**

In contrast to defects, inventory deterioration is not caused by direct activities in the factory, but rather by policies that lengthen of the holding time of sensitive material in the factory, and ambient conditions, which accelerate the material deterioration process (compare Figure 27).

Many of the principles to prevent inventory deterioration are in agreement with lean manufacturing principles, e.g. reducing inventory levels, holding times, lot sizes, and raw material order quantities. Consequently, a goal conflict occurs when minimizing inventory deterioration through smaller lot sizes and reducing setup material losses (e.g. startup losses, cleaning materials).

Interestingly, the first-in-first-out sequence of order processing, a principle of lean manufacturing, may not be fitting to every product deterioration profile. For some materials which deteriorate at a lessening rate over their holding time (concave deterioration function), last-in-first-out policy reduces the overall shrinkage. Since first-in-first-out dictates that two consecutive processes process orders in the same sequence, last-in-first-out may offer some processes the ability to optimize their order processing sequences to reduce setups.

### 5.1.3 Transport Loss

The following section embellishes on the causality of transport loss, focusing on its differentiation from process defects and inventory deterioration.

#### 5.1.3.1 Machine-Induced Transport Loss

**Poor vehicle or handling apparatus design:** Poor matching of the product to the vehicle or conveyor type may cause product damage, e.g. moving oversized products with a forklift, or losing bulk material off the sides of conveyor belts.

**Poor equipment condition:** Vehicles in poor condition are susceptible to breakdowns or excessive vibrations and are more likely to damage material (UN FAO 1989, pp. 77).

**Poor infrastructure:** Generally the longer distances travelled, the higher the risk of damage (Cheng et al. 2000, pp. 332). Often this is dictated by the infrastructure of the factory or the existing conveyance systems (Garvin 1988, pp. 147). Poor conditions of pathways (bumps) and obstacles on the route increase the risk of spillage (IRAM 2013, pp. 103).

#### 5.1.3.2 Employee-Induced Transport Loss

**Poor training or employee negligence:** Poor training or negligence of forklift drivers is responsible for most factory accidents with material damage (Ross 2015). Driving higher speeds to finish jobs quicker is a leading cause (UN FAO 1989, pp. 77).

#### 5.1.3.3 Material-Induced Transport Loss

**Material is fragile:** Fragile products experience particularly high levels of loss in transport, e.g. glassware and baked goods (Dris et al. 2004, pp. 231).

#### 5.1.3.4 Method-Induced Transport Loss

**Poor housekeeping:** Obstacles in plant corridors due to poor housekeeping can cause accidents and lead to damaged product (Stone 2012).

**Material handling method:** Longer distances and frequent hand-overs increase the risk of material loss (Tompkins 1988, pp. 846; Cheng et al. 2000, pp. 330). Adequate packaging methods for transport are necessary to protect the finished product from unwanted contact (Tompkins 1988, pp. 846).

#### 5.1.3.5 Transport Loss Causation

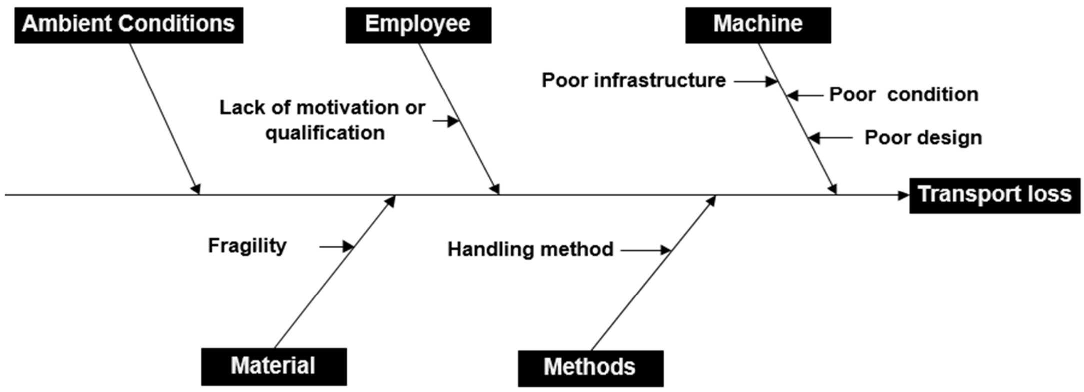



**Figure 28: Causation of transport losses**

Unlike inventory deterioration, transport losses describe material damage through weaknesses in vehicle condition, route design, handling methods, and human error in combination with fragile materials (see Figure 28). Ambient conditions and material characteristics play a lesser role, due to the relatively short duration of logistical processes.

### 5.1.4 Trim Loss

Off-cut or trim loss is the useless remainder material after mechanical separation of a workpiece geometry from raw material, or after cutting a raw material to the appropriate length, e.g. sheet metal, extruded plastics, wood, rubber, foils, and fabrics. The many causes for trim loss are discussed in the subsequent sections.

#### 5.1.4.1 Machine-Induced Trim Loss

**Limitations of cutting technologies:** Not every cutting technology has the ability to make both parallel and nonparallel cuts with respect to material edges (guillotine cuts and interlocking cuts), limiting the number of possible optimized patterns. Some machines may limit the number of parallel guillotine cuts due to the number of knives in the machine (Dyckhoff et al. 1985, pp. 66). Optimal cutting plans may require multiple knife changes (setups) (Kallrath et al. 2014, pp. 374). The ability to “skive” or join smaller geometries, combining cutting remainders to generate a full-value part in a secondary sewing or joining process, can potentially reduce trim loss (Arbib et al. 2005, pp. 618).

**Limits of computer aided optimization software**: Depending on the quality of nesting algorithms, the resulting cutting pattern yields considerably less trim loss than manually generated cutting patterns (Östermark 1999, pp. 623). Complex cutting plans to reduce trim loss may however result in longer operation times and reduce machine output (Östermark 1999, pp. 623).

#### 5.1.4.2 Employee-Induced Trim Loss

**Employee experience:** In the case of manual nesting of part geometries, the experience and qualification of the operator plays a role in the sheet utilization.

#### 5.1.4.3 Material-Induced Trim Loss

**Dimensional differences in raw material and order size:** Varying the size and shape of incoming materials to better fit the sizes needed by the customer reduces trim loss (Venkateswarlu 2001, pp. 166; Saraç et al. 2003, pp. 44). Setting product geometry specifications to better fit the generic raw material geometries on the market (typically rectangular) can substantially reduce trim loss (Spies 1959, pp. 42; Dyckhoff et al. 1985, pp. 66).

If bulk raw material is cut to generic stock-sizes before cutting to customer specifications, choosing a set of stock sheet sizes compatible with customer specification sizes can reduce trim loss, but may increase inventory levels through larger stock sheet variety (Agrawal 1993a, pp. 424). A minimum trim loss per stock sheet is unavoidable therefore cutting multiple geometries from larger stock sheets lessens trim loss (Agrawal 1993b, pp. 422).

The multi-dimensionality of geometry differences between stock sizes and order sizes (1, 1.5, 2, 2.5 or 3 dimensions) increases the difficulty of the optimization problem and the likelihood of material loss (Dyckhoff et al. 1985, pp. 62).

Physical properties within the material structure may require a minimum distance between neighboring cuts, e.g. maintaining minimum distances in glass-cutting (Dyckhoff et al. 1985, pp. 65).

5.1.4.4 Method-Induced Trim Loss

**No freedom to optimize product mix:** Scheduling geometrically complementary product mixes and permitting deviation from schedules to lessen trim loss can fully utilize stock sheets (Israni 1984, pp. 208; Venkateswarlu 2001, pp. 166). Policies to only complete single-customer orders at once may hinder favorable product mix (Dyckhoff et al. 1985, pp. 65). Allowing make-to-stock product geometries to be cut can create favorable product mixes, although increasing the inventory of standard parts (Israni 1984). Lot-sizing policies that are aligned with nesting patterns and sheet sizes support trim loss minimization and low inventory levels (Spies 1959, pp. 42).

**No-restocking policy for cut sheets:** Policies discouraging saving partially cut sheets for later use, due to space constraints, increase the trim-loss of cutting operations (Venkateswarlu 2001, pp. 166).

#### 5.1.4.5 Trim Loss Causation

Combining the causes discussed in the previous sections, Figure 29 presents an overview of the factors influencing the quantity of trim loss that occurs in manufacturing. It is clear that the discrepancies between raw material dimensions and workpiece specifications is the cause of trim loss, although cutting policies and optimization methods affect the degree of loss.

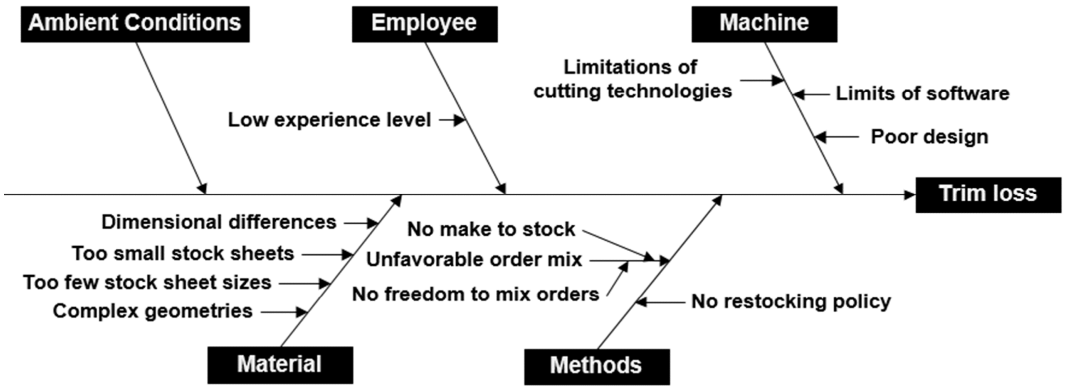



**Figure 29: Causation of trim loss**

To utilize a stock-sheet fully, generic geometries may be produced, which are held as inventory, or partially used sheets may be restocked, increasing holding costs. Alternatively, parts for anticipated orders can be made, increasing both inventory costs and the risk of scrapping parts if the order is not placed. Order sequence flexibility presents the best conditions for trim loss optimization though this may result in higher inventory levels and unfavorable product variant sequences elsewhere in the process chain with respect to defects.

Pursuing the goal of reduced trim loss requires both heightened scheduling efforts and the use of computer-supported optimization, presenting additional costs for manufacturers.

### 5.1.5 Chips

Chips describe the unusable remaining material that occurs in a separation process when a single workpiece is cut from a raw workpiece. The quantity and the shape of chips in cutting processes has been analyzed in depth, as they are also a means of transferring heat away from the tool and workpiece (Patterson et al. 1965, pp. 48; DeVries 1992, pp. 39). Unlike trim-loss, the mass of chips is assumed roughly constant for a given operation and product variant, as shown in Figure 30. While the quantity of the chips cannot be influenced at an operative level, methods to properly sort metal chips increase the scrap value thereby mitigating the material waste cost (Gobrecht 2009, pp. 207).

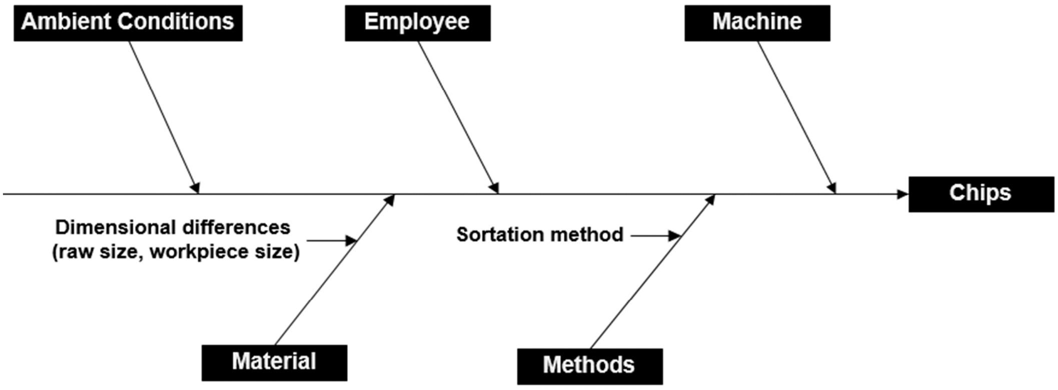



**Figure 30: Causation of chips**

### 5.1.6 Byproducts

Byproduct describes leftover material after a chemical or mechanical separation of an unusable material mass, which is different from the desired product in chemical composition or physical characteristics. These are frequently seen in each segment of the process industry, from chemical byproducts to food-processing byproducts. Some byproducts are flexible in their quantity and quality, such that their quantities can be changed by the following means (Oenning 1997, pp. 57).

- changing process inputs (substitution)
- using an alternative transformation process
- changing the quality limits of the desired product
- adjusting process parameters or conditions

However, other byproducts are deemed fixed or rigid if their quantity is determined by upstream processes or nature, e.g. eggshells in liquid egg processing.

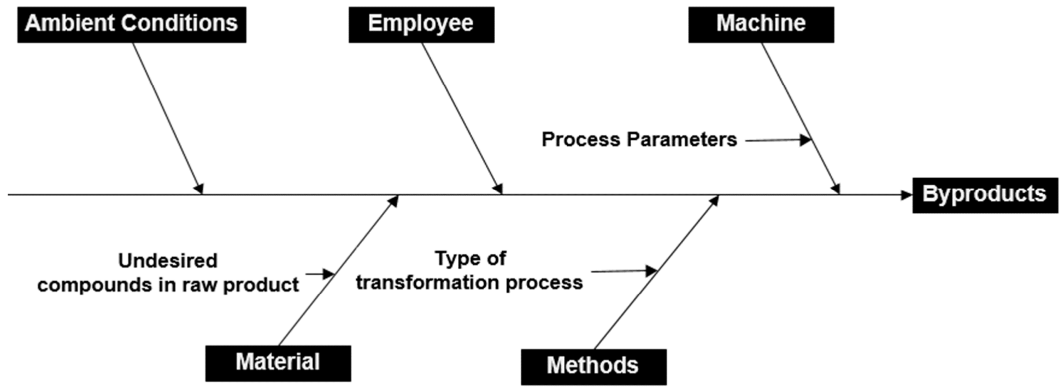



**Figure 31: Causation of byproducts**

As shown in Figure 31, the means to change the given byproduct quantities involves changes to the transformation technology, its parameters, and the product specifications themselves. The effects of operative decision-making (e.g. lot sizes, sequences, which employees) are of lesser importance. Since chemical reactions take place under isolated conditions, changes in ambient conditions within the production building are also insignificant. Changes to process parameters are strategic decisions, which are not considered in this work. For that reason, byproducts are assumed a fixed material waste form within this thesis.

### 5.1.7 Auxiliary Materials: Joining and Coating Materials

The term, auxiliary material, describes secondary materials applied to a workpiece to increase its value. Typical examples are coatings (e.g. paint, enamel) or joining materials (e.g. welding material, glue). This section addresses auxiliary material losses in manufacturing processes, auxiliary material losses in storage or transport are addressed in 5.1.2 and 5.1.3.

#### 5.1.7.1 Machine-Induced Auxiliary Material Waste

**Application technique and system design:** In direct application (e.g. dip painting or flooding) fewer losses to the surroundings occur than in indirect application (e.g. sprays, mists) (Goldschmidt et al. 2002, pp. 496). However the achieved coating characteristics and part size compatibility vary by application method (Blesl et al. 2013, pp. 139).

Overspray quantities, or mist losses to the surroundings depend the technologies, product designs, part arrangement on racks, or introducing recovery equipment (Obst 2002, pp. 27). Using electrostatic pistol application, transfer efficiencies of between 30-70% can be attained (Dreyhaupt 2013, pp. 211).

In direct application, material adhesion to racks and baskets amount to an average transfer efficiency of about 85% (Dreyhaupt 2013, pp. 211). In dip painting and flooding, large paint reservoirs may need to be discarded regularly to limit the effects of contamination over time (Lambourne et al. 1999, pp. 429).

#### 5.1.7.2 Employee-Induced Auxiliary Material Waste

**Heavy-handed paint dispensing:** Employee overestimation of paint quantities for production orders caused 200%-400% higher paint consumption than automated dispensing systems in a study of a process where paint remainders are discarded. The authors cited lack of skill and lack of cost or environmental-consciousness as a cause (Nolte 1998, pp. 107–108).

#### 5.1.7.3 Method-Induced Auxiliary Material Waste

**Lot-sizing and job bundling:** If it is company policy to discard excess paint in the last color before a color changeover, running smaller lot-sizes increases the discarded paint quantity over time. Bundling production jobs by color (e.g. all white refrigerator doors on Tuesday) reduces the number of color changes.

**Reuse policy:** Company policies dictate if paint remainders can be reapplied later. If the remainders are collected, the paint waste due to over-dispensing is eliminated.

**Maintenance and leaks in machines:** Leakages can also occur if maintenance intervals are infrequent in the recirculation system or dispensing system.

### 5.1.7.4 Summary of Auxiliary Material Waste Causation

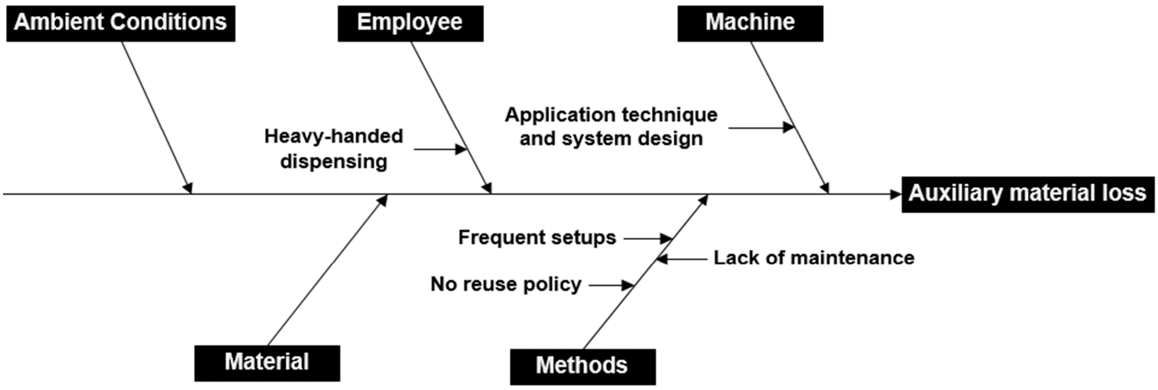



**Figure 32: Causation of auxiliary material loss**

The causes of auxiliary material loss are compiled in Figure 32. Auxiliary materials are wasted both in the application process as well as when excess material is brought into the system and not fully utilized before the next setup. Application losses are predefined by the application technique, product design, rack design, and overall system design and therefore assumed to be fixed in this thesis.

Depending on reuse policy and the degree of automation this auxiliary material, significantly different quantities of auxiliary materials are lost. In the case of manual dispensing, the quantity of over-dispensed paint that is discarded at setups is assumed to vary based on employee qualification and motivation.

Since auxiliary materials are frequently processed in enclosed areas under controlled conditions, only in rare cases can changes in the factory climate affect auxiliary material losses.

### 5.1.8 Closed-loop System Operating Materials with Workpiece Contact

To ensure that process operating materials are contained, closed-loop reservoir systems have been developed. Examples include cutting fluids reservoir systems, quenching materials after heat treatment, and industrial degreasing operations. Although these systems recovers a large portion of the operating material flow after application to the workpiece, a non-negligible portion remains on the workpiece, on the surrounding surfaces or is lost to the atmosphere. Figure 33 demonstrates this phenomenon on the example of a decentralized cutting-fluid system.

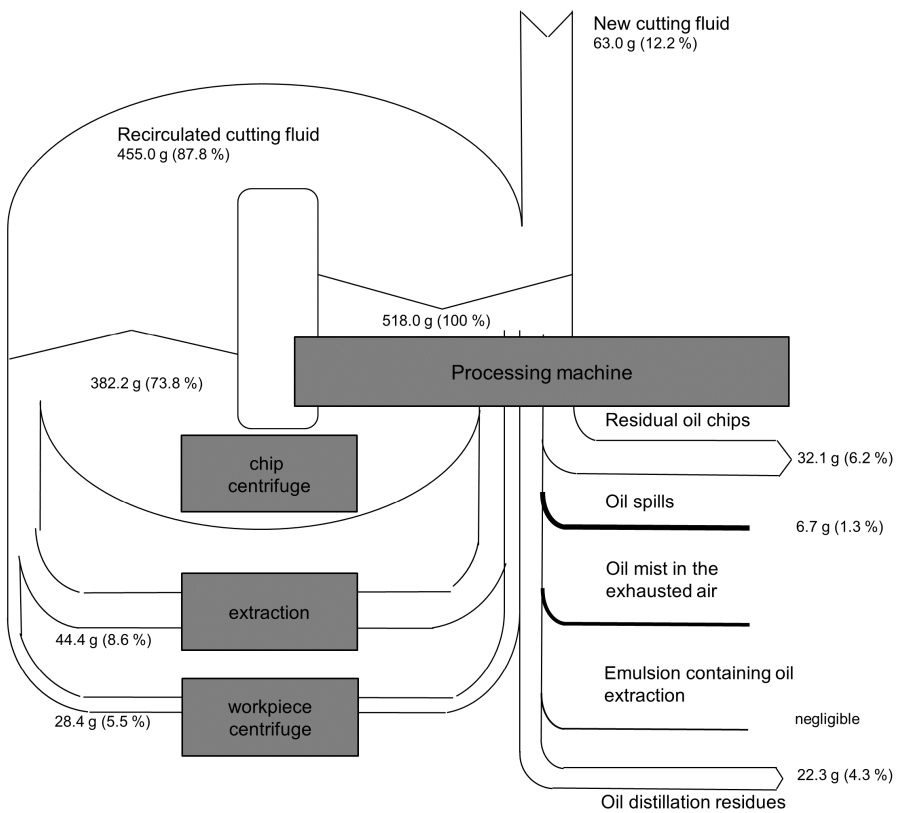



**Figure 33: Exemplary losses in a cutting fluid system (Petuelli 2002, pp. 24)**

#### 5.1.8.1 Machine-Induced Material Loss

**Process conditions:** Processing conditions (e.g. spindle speed, workpiece diameter, feed rate) influence the quantity of cutting-fluid loss as mist in cutting operations (Adler et al. 2006, pp. 7). Some cutting conditions may be

suitable for minimal lubrication or dry cutting, while others are not compatible with these methods (Gernsheimer 2012, pp. 48–49).
**Process technology:** The length and design of the drip-off area for wet workpieces and chips determines the extent of drag-out losses (Petuelli 2002, pp. 23–24).

#### 5.1.8.2 Material-Induced Material Loss

**Workpiece geometry:** Workpiece depth and roughness can increase drag-out (Kraft 2012, pp. 134). The product geometry and cutting conditions dictate the amount of material lost to chip drag-out (Klocke et al. 2007, pp. 271).
**Material selection:** Evaporation losses vary depending on the chemical composition of the material (DIN EN 31007 2003, pp. 6).

#### 5.1.8.3 Ambient Condition-Induced Material Loss

**Air quality:** Biological contamination and the growth of fungi cause loss of functionality in cutting fluids and disposal of reservoir contents (Filipovic 1998, pp. 389).

#### 5.1.8.4 Method-Induced Material Loss

**Infrequent activity:** Idling of cutting-fluid systems for too long can enable biological contamination, often noticeable over a weekend without use.
**Too little maintenance:** Loss of functionality due to biological contamination can be negated through regular maintenance activities.
**Quality control policies:** If defect rates are too high in a cutting operations, the contents of the cutting-fluid reservoir may be purged (Filipovic 1998, pp. 389).

#### 5.1.8.5 Summary

Summarizing the causes of losses in closed-loop operating material systems with workpiece contact, the impact that the workpiece material properties and the workpiece geometry have as a primary expulsion mechanism for operating materials from their closed loop system is clear, as shown in Figure 34.

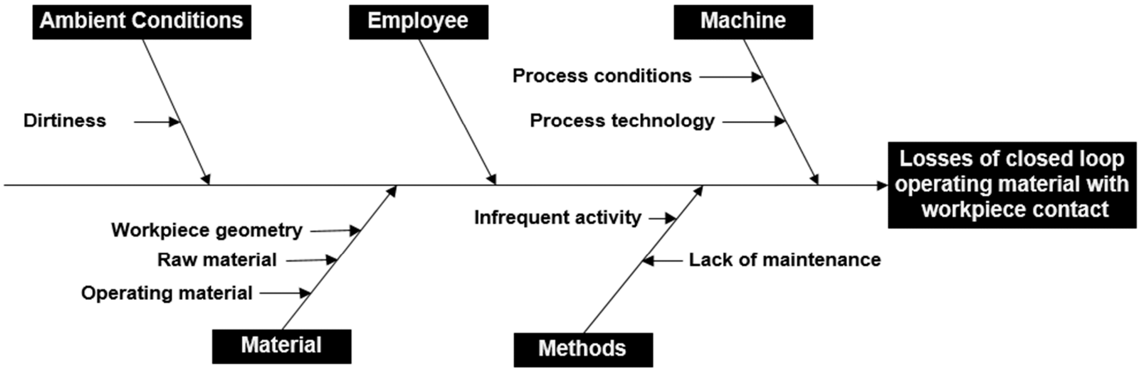



**Figure 34: Causation of losses in closed-loop operating material systems**

### 5.1.9 Closed-loop System Operating Materials without Workpiece Contact

Closed loop system operating materials that are not exposed to workpieces or the product generally have fewer expulsion mechanisms. A common example is the use of lubricants in the bearings of industrial machinery for lubrication and cooling purposes.

#### 5.1.9.1 Machine-Induced Consumption

**Number of application points (e.g. number of bearings and machine components):** The quantity of lubrication points, as well as the lubrication specification dictate how much lubrication is used.

**Method of application:** Depending on the design of the system and the method of application (e.g. open centralized systems, air-oil lubrication systems, single point lubrication) the total lubricant consumption can vary substantially (Bloch 2009, pp. 170).

**Degree of automation:** Automatically dispensed lubrication is less material-intensive than manual application (Bloch 2009, pp. 169).

#### 5.1.9.2 Employee-Induced Consumption

**Heavy handed and inattentive lubrication:** If manual application is used, material can easily be over-dispensed or spilled (VDI 2897 , pp. 2).

5.1.9.3 Method-Induced Consumption

**Overloading machines:** Frequent and heavy machine loading leads to accelerated lubricant wear and degradation, making oil changes more frequent (Bloch 2009, pp. 177).

**Infrequent Maintenance:** Leakages of lubricants may be linked to infrequent machine inspections.

**Too frequent oil changes:** The chosen interval for lubrication service and its priority with respect to other goals plays a decisive role in the total consumption.

**Manual or semi-manual handling:** There are multiple sources of losses if container transfers are performed manually, including spills and contamination (VDI 2897 , pp. 12),

5.1.9.4 Summary

Because the operating materials are not in direct contact with the processed workpiece, the workpiece cannot serve as an expulsion mechanism from the closed loop system, and therefore product geometry and material properties play a only an indirect role in the quantity consumed (see Figure 35).

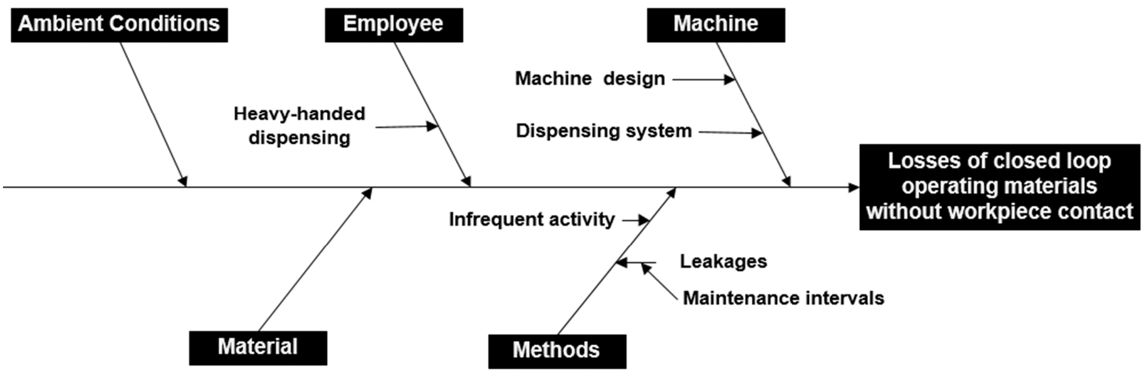



**Figure 35: Causation of CLOM consumption without product contact**

5.1.10 Single-use Operating Materials: Cleaning Materials

Industrial cleaners and solvents are used both in value-adding processes (e.g. cleaning printed circuit boards before coating), but also for machine rinsing and housekeeping purposes within the factory. Furthermore, cleaning solvents are usually discarded after use, with few exceptions.

#### 5.1.10.1 Machine-Induced Cleaning Solvent Consumption

**Process requirements:** To maintain machine operability and product quality, a base-line solvent consumption may be necessary, though this can often be replaced by hot water (Kohli et al. 2011, pp. 213).

**Machine sizes and design:** Large machines and spacious work areas collect more dust and dirt, and therefore require more cleaning solution consumption. Machine enclosures for dirt-emitting machines reduce the area requiring cleaning and the expenditure of cleaning materials. Modular and mobile machines, that can removed from the vicinity when out of use, prevent clean, unused machine components from getting dirty (Henry 2013, pp. 55).

#### 5.1.10.2 Employee-Induced Cleaning Solvent Consumption

**Heavy handed dispensing:** Depending on the skill and the motivation of employees, the quantity of cleaning materials used in manual cleaning processes may vary.

**Low tolerance for dirt:** The cleaning interval is often determined by the dirt tolerance of the shop floor management or the operators themselves.

#### 5.1.10.3 Material-Induced Cleaning Solvent Consumption

**Product is poorly designed:** Awkwardly designed geometries and surface finishes trap more dirt and collect more dust.

**High residue processing agents:** Processing agents that leave a heavy residue on the product cause more cleaning product consumption (Kanegsberg 2011, pp. 24).

**Cleaning required at setups to remove previous material:** Forming or coating processes often require flushing the machine to purge residues from the last product variant (Henry 2013, pp. 4). The more raw or auxiliary material residues in the system, the higher the cleaning solvent consumption (Nolte 1998, pp. 108). The size of the material reserves and the length of piping determine the extent of the flushing effort. Instead of cleaning materials, raw materials are used to flush the material residues out of the machine in some processes (e.g. beer brewing) (Henry 2013, pp. 54).

**Leakages:** Leakages from lubricant systems or auxiliary material systems can cause an unplanned clean-up activity and therefore more cleaning solvent consumption.

**Material-related disturbances:** Severely damaged defects or a machine breakdown may warrant a machine clean-up.

#### 5.1.10.4 Method-Induced Cleaning Solvent Consumption

**Cleaning policy:** If more time for cleaning is available or if hot water is available for use, it may be possible to clean certain machines without abrasive solvents (Stahlmann et al. 2013, pp. 203). Drawbacks include more employee time in non-value adding activities or higher water and energy consumption.

**Lot-sizing and order bundling:** If flushing is required at setup (see 5.1.10.3), small batch sizes, or product variant sequences of differing raw and auxiliary material requirements cause more cleaning material consumption.

#### 5.1.10.5 Summary of Cleaning Solvent Consumption

A number of influence factors determine the frequency and scope of cleaning activities, and respectively the quantity of cleaning solvents consumed. These influence factors are summarized in Figure 36.

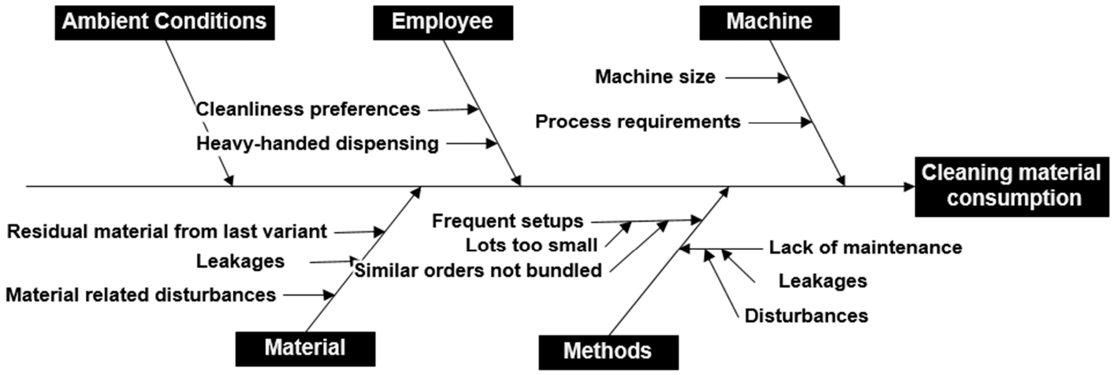



**Figure 36: Causation of cleaning material consumption**

### 5.1.11 Single-use Operating Materials with Workpiece Contact

**Plugs and covers:** Surface treatment processes (e.g. coating), which only treat a selected area of the workpiece, may require disposable covers or plugs to protect the other areas of the product. Selective processing technologies make it easier to complete these processes without affecting the rest of the product. Alternatively, changing the workflow of the product and performing the process on a single component or subassembly before assembly may be an option, although this approach may require special tooling or clamping devices.

**Intermediate packaging** is utilized to protect the product during transport and storage and therefore used to negate the effects of inventory shrinkage. Intermediate packing comes in reusable form, or may be disposable. Sensitive products and harsh transport conditions within the factory, as discussed in Section 5.1.3, are reasons for using packaging materials.

For these two cases, an Ishikawa diagram is derived in Figure 37.

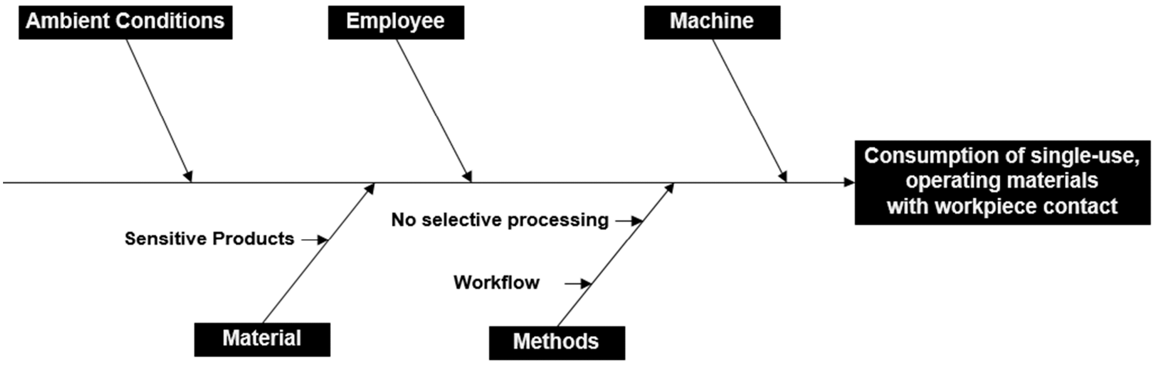



**Figure 37: Causation of single-use operating material consumption**

## 5.2 Material Waste-Causing Activities

As shown in the Ishikawa diagrams, the prevalence of activity-triggering influence factors in academic and practical literature reinforces the connection between material efficiency and the avoidance of wasting activities and events. These activities and events are shown in Table 9 with their corresponding material waste forms, as identified in the Ishikawa diagrams. In the following sections, the term "activity" will be used to describe both planned activities as well as unplanned events for brevity.

Some of the activities are already depicted in operating-state-based manufacturing simulations (Section 4.2), while others have not previously been modelled. To investigate how well the operating states represent material-wasting activities, Haag's set of operating states, arguably the most extensive set, is compared with the identified material-waste activities. These include *work, warmup, wait, block, error, setup, off/standby*, and *save* (Haag 2013).

**Table 9: Linkage of waste forms to planned and unplanned activities**

| | Planned activities | | | | | | | | Unplanned activities | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material waste form | Processing interval | Stock material unit replenishment | Destructive testing | Transport | Setups | Housekeeping | Maintenance | Shut-offs and Startups | Machine breakdown | Machine idling | Material aging interval |
| 5.1.1 Process defects | ● | ○ | ● | ● | ● | ○ | ○ | ● | ● | ● | ○ |
| 5.1.2 Shrinkage | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● |
| 5.1.3 Transport loss | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 5.1.4 Trim loss | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 5.1.5 Chips | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 5.1.6 Byproducts | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| 5.1.7 Auxiliary materials | ● | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ● |
| 5.1.8 CLOM with workpiece contact | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ● |
| 5.1.9 CLOM without workpiece contact | ● | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ |
| 5.1.10 Cleaners | ● | ○ | ○ | ○ | ● | ● | ○ | ○ | ● | ○ | ○ |
| 5.1.11 Packaging and protectors | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

●= Material waste form linked to activity ○= No linkage

**Workpiece or batch processing:** Material consumption or waste occurring with every workpiece or machine batch could be modelled in a work-state on the respective machine with a lump sum per piece or batch, or as a waste rate analogous to power consumption.

**Stock-material unit replenishment:** Haag's set of operating states neglects to consider the activity of removing material lost at the end of a material stock unit (e.g. a stock sheet or coil remainder). The act of removing and discarding the remainder material may take place during processing without interruption (work-state), when the machine feed is empty (wait state) or during setup procedures (setup state). The most logical approach would be to model this waste as occurring in a lump sum when transitioning into an idle or setup state. However, stock material remainders are not removed during every wait or setup state, only when the machine is nearly starving, i.e. the stock unit is almost completely consumed, or needs to be changed to process another order type. Therefore a more complex operating state logic is required to differentiate between starving conditions, and other sources of machine waiting (i.e. employee absence, no orders, material not delivered).

**Destructive testing:** testing operations are not explicitly addressed in the machine-operating state approach, though they could be added by modelling testing equipment as a machine. Destructive testing would occur in the work-state of a testing machine. The length and frequency of testing intervals would depend on testing policy.

**Transport intervals:** With the exception of fully automated transport systems, logistical and handling operations are frequently neglected in operating-state-based modelling due to the low energy consumption in manual handling operations and the extent of employee influence (e.g. forklift energy consumption). Transport activities however cannot be neglected in material efficiency modelling. Machine operating state logic applies very loosely to transport activities, as some material waste may occur due to the dynamics of operating state transitions (e.g. sudden breaking modelled as wait state or errors). However, there is no indication in literature that setup activities and startups of transport equipment and vehicles are material intensive. Additionally the effort of conceptualizing an operating state-logic of a human driven system may exceed the benefit of modelling these operations. Therefore a lump sum per transportation activity is assumed adequate in detail.

**Setup intervals:** Due to the difference in materials consumed during setup procedures to those in normal operations (e.g. cleaning materials, testing materials), the two operating states need to be distinguished. However, the shutdowns and startups preceding and following the setup procedure may be more material intensive than the setup itself, warranting consideration of the transitions between operating states. State transitions are ignored with the exception of machine warm-ups in energy efficiency modelling. Depending on the combination of successive product variants, the amount of material waste occurring may vary (e.g. light clean-up vs. heavy clean-up). Therefore the lump material waste quantities per transition cannot be assumed constant.

**Housekeeping intervals:** machine-centric operating-state-based simulation methods neglect the material consumed in housekeeping and secondary activities in the direct peripheral of the machine. These cannot be integrated into the operating state logic, as they are performed manually independent from the machine's operating state. For that reason, modelling housekeeping as a lump sum per activity or as a waste rate over the duration of the activity is suggested.

**Maintenance intervals:** maintenance activities requiring material consumption (e.g. cleaners, lubricant disposal and replenishment) can either take place in an unplanned repair activity (analogous to Haag's error-state), or in a planned preventative maintenance activity. The latter option is not featured operating-state-based modelling. During a planned maintenance activity, the machine may remain in an idle state or be turned off. To account for the additional material consumption of planned maintenance, an additional operating state is suggested. Similarly to idle or off, it is assumed that shutdown and startup loss respectively immediately precede or follow the planned maintenance state.

**Machine shutdowns and startups:** Since defects occur at increased levels during machine startups and shut downs, transitions between the operating states work and off cannot be neglected.

**Machine idling:** To account for startup losses in processes where the machine is never fully shut-off, as well automatic material disposal after prolonged inactivity (e.g. automatic purging of granulate in injection molding after inactivity), an idling state needs to be modelled.

**Machine breakdown intervals:** machine error states are associated with higher material waste rates than idle states due to the unplanned deviation of process parameters. Thus, it is necessary to differentiate between idling and breakdowns, as Haag does for energy consumption.

**Material aging interval:** Material loss due to inventory deterioration has been ignored in resource efficiency simulations, since the machine is not directly responsible. Since inventory deterioration has been modelled in other applications as a function of fixed or variable shelf life, exceeding the shelf life of a product could be modelled as a peripheral event, or the activity of inspecting inventory shelf-life can be modelled as a peripheral activity. To model a variable shelf life, the storage location or ambient conditions may need to be modelled.

Overall, representing machine behavior with a set of operating states and their transitions covers a number of the material waste causing activities, but frequently not in adequate detail. For that reason, this approach must be supplemented by the modelling of peripheral activities and by varying the waste rates or waste quantities of an operating state depending on a number of conditions, which will be described in the next section.

## 5.3 Types of Influence Factors

After establishing which material waste causing activities are relevant through the Ishikawa diagrams, the individual causes and influence factors can be group by the mechanism, with which they affect the amount of waste occurring in the system. Certain factors clearly trigger material-causing activities or dictate in which intervals the activities must be performed. Other factors influence the duration of the activities. A third set influence the material waste quality per activity, i.e. what type of material waste occurs.

Other factors affect the quantity of material waste per activity. Each of the four types are discussed in the next section.

### 5.3.1 Activity-Triggering Factors

One way the described influence factors from the Ishikawa diagrams influence the aggregate material waste in the factory is by triggering material waste-causing activities.

Examples from the influence factors discussed in 5.1 that influence the frequency of activities and events are briefly described below.

**Disposal policy:** Internal and external policies dictate in which intervals or under which conditions materials are discarded, e.g. if paint remainders or half-cut stock sheets can be saved for future jobs. This influences the amount of waste occurring during stock piece replenishment and in setup procedures.

**Dispatch policy:** The rhythm and sequence in which orders and material are released for processing, e.g. in large batches, determines how frequently undesirable machine states (e.g. idling, setups) occur.

**Employee motivation:** Employees can trigger machine idling or machine breakdowns through their absence or negligence, depending on their role in the manufacturing process.

**Housekeeping policy:** Housekeeping policies dictate the minimum frequency for cleaning activities.

**Maintenance intervals:** The frequency of maintenance activities and their timing, i.e. bundled together, determine how frequently machine shutdowns and startups occur.

**Poor machine condition:** Deteriorating machine and tool condition are two driving factors in the frequency of machine breakdowns. Poor machine condition may also lead to more frequent repair and preventative maintenance activities.

**Lot sizes:** Lot sizes dictate how often the machine will be shutdown, setup and started-up with for a different successive product variant. Companies may have minimum lot size policies to lessen the frequency of these activities.

**System loading:** how frequently a job is assigned to a machine contributes to the number of state transitions (idling, setups, shutdowns), and how much time remains for other activities, including planned maintenance.

**Unsuitable ambient conditions:** Unsuitable ambient conditions may cause machine breakdowns or material aging.

As these influence factors determine how frequently activities occur, they should be included in the operating state logic, i.e. the logic that dictates which operating state is active at each point in time, or under which conditions peripheral activities occur.

### 5.3.2 Duration-Dictating Factors

For some activities, material waste occurs at a steady rate over time, rendering the activity duration a decisive factor in the total material consumption. Some influence factors can increase aggregate material waste by prolonging the duration of these activities.

Examples from the influence factors discussed in 5.1 include:

- Lot-sizes: The duration of the work-state of a machine may be prolonged by minimum lot size policy, thereby exceeding the requirement of a customer order. If the surplus parts are not sold, the amount of material waste increases disproportionally to the activity.
- Quality rates: producing poor quality increases the duration of the work-state to process or rework certain parts, increasing the operating and auxiliary material consumption for processing an order.
- Employee motivation: Employee motivation levels not only influence the occurrence of idling and breakdowns but also their duration.

- Employee qualification: Employee qualification and experience levels may influence the duration of maintenance and setup activities.

### 5.3.3 Linking Factors

The linkage between material waste forms and activities may be flexible in some cases. The decision to reuse or dispose of remainders from stock sheets (trim loss), auxiliary, and operating materials is generally within the authority of factory management, while the reuse of other waste materials, e.g. salvaging defects requires coordination with product engineering and process planning functions.

The influence parameter, disposal policy, describes whether coupling an activity with material waste is necessary:

- Disposal policy: determines if a setup activity is coupled with flushing the machine and disposing of residual material, or if partially cut stock sheets can be reused. Similarly, the decision if intermediate packing should be discarded depends on the disposal policy.

### 5.3.4 Quantity-Determining Factors

Certain influencing factors influence the quantity of material waste per activity or per time-unit, without causing an activity to occur or influencing its duration. These factors serve to explain varying waste rates for identical operating states or changes in the waste rate over the course of time. These influence factors are deemed as “waste amplifiers” for that reason.

- Employee qualification and cost-consciousness: Employee qualification and cost-consciousness may explain significantly higher material waste quantities or material waste rates for performing the same activities for similar durations.
- Lot sizes: While the startup losses for a production lot are fixed per lot and can be modelled as a fixed quantity per machine startup, the amount

of process defects occurring at the end of long production runs due to machine fatigue exemplifies an increased material waste rate for a large lot size.

- Poor machine condition: While the occurrence of part-processing activities and their duration may be identical, poor machine condition may lead to higher material waste rates or waste quantities.
- Unfavorable product variant or process batch sequences: Although the processing duration and frequencies of activities (startups and setups) for different product variant sequences are identical, the amount of material waste caused when running unfavorable product variant sequences may be noticeably higher; therefore, unfavorable product variant sequences are considered a waste amplifier.
- Unsuitable product variant / machine combination: For work centers with multiple, interchangeable but not identical machines, the assignment of a product variant to a less suitable machine may explain the difference in material waste quantities under the same processing conditions.
- Unsuitable ambient conditions: Changes in air quality, possibly stemming from the occurrence of material waste, may explain differences in the material waste rates or material waste quantities for the same activities.
- Long holding time: long material holding times in the factory may cause machine parameter deviations when processed or larger amount of inventory disposal in the sudden event of technical obsolescence or spoilage.
- Disadvantageous product mix in pipeline: trim loss optimization is contingent on the availability of a mix of geometrically complementary orders. Similarly, some batch oven processes yield lower defect rates

when the part geometry mix allows for optimal temperature distribution.

## 5.4 Influence Factors within Operative Management

Reviewing the influence factors described in sections 5.1 and 5.3, some fall in the authority of operative decision makers at a factory site, while the second set requires tactical or strategic measures, exceeding the authority of OM.
The factors that are within the realm of OM are shown in Table 10 and described below:

- Dispatch policy, the order with which materials are released for processing or shipping within a factory is within the authority of operative decision makers,
- Disposal policy, or the definition of criteria for retiring operating materials from use and discarding paint or stock sheet remainders, is assumed well within the reach of operative decision makers. The disposal of inventory exceeding its shelf life is within the authority of operative management if not regulated by law.
- Employee cost-and environmental consciousness and employee motivation can be determined by selectively hiring candidates who embody company values, by training employees, and using incentive systems. Employee qualification can be increased by training employees and utilizing job rotation systems.
- Maintenance intervals: Infrequent maintenance can be remedied by planning more frequent maintenance activities, increasing staff size, and prioritizing maintenance. Similar to housekeeping intervals, the resulting material consumption or prevented material loss is a production-site-specific decision within the authority of OM.
- Lot sizes and system loading is the sole responsibility of production scheduling. Analogously, unfavorable product variant sequences on a

single machine and the assignment of unsuitable product variants to machines are based on a production schedule.

- Unsuitable ambient conditions, including poor air quality, can also be influenced by operative management, and therefore are considered within the authority of OM.

**Table 10: Influence factors within the authority of OM**

| Within the authority of OM | Affected waste forms |
|---|---|
| Dispatch policy (see 5.1.2.4) | inventory shrinkage |
| Disposal policy (see 5.1.7.3) | auxiliary materials – CLOM without workpiece contact – inventory shrinkage – trim loss – single use operating materials |
| Employee cost-and environmental consciousness (see 5.1.7.2) | auxiliary materials – cleaning materials – CLOM without workpiece contact |
| Employee motivation (see 5.1.1.2) | inventory shrinkage – process defects – transport loss |
| Employee qualification (see 5.1.1.2) | process defects |
| Infrequent maintenance (see 5.1.1.5) | auxiliary materials – cleaning materials – CLOM – process defects –transport loss |
| Housekeeping policy (see 5.1.3.4) | cleaning materials – transport loss |
| Lot-sizes (see 5.1.1.5) | auxiliary materials – cleaning materials – inventory shrinkage – process defects – trim loss |
| Poor equipment condition (see 5.1.1.1) | cleaning materials – process defects – transport loss |
| System loading / frequency of use (see 5.1.1.5) | process defects – closed-loop operating materials |
| Unfavorable product variant sequences (see 5.1.1.5) | cleaning materials – process defects – trim loss |
| Unsuitable ambient conditions (see 5.1.1.3) | CLOM with workpiece contact – inventory shrinkage – process defects |
| Unsuitable machine / product variant pairing (see 5.1.1.5) | process defects |

The set of influence factors beyond the limits of operative decision-making include any changes to the product structure (product specification and raw and auxiliary material selection) or the transformation processes used (process specifications, operating material selection). Similarly, any changes to the system design of machines, handling technologies, or warehousing infrastructure are out of reach for an operative decision maker. Upstream organizational constraints, e.g. the lack of a product quality planning function may also influence waste.

These influence factors and the affected waste forms are summarized in Table 11.

**Table 11: Influence factors exceeding the limits of OM**

| Exceeding the authority of OM | Affected waste forms |
|---|---|
| Material selection (see 5.1.8.2) | CLOM with workpiece contact - process defects |
| Organizational constraints (see 5.1.1.5) | process defects |
| Poor system design (see 5.1.1.1) | auxiliary materials - byproducts- cleaning materials - CLOM - inventory shrinkage - process defects- transport loss- trim loss |
| Process specification (see 5.1.7.1) | auxiliary materials – byproducts – CLOM with workpiece contact - cleaning materials - single use operating materials |
| Product specifications (see 5.1.4.3) | byproducts- chips- cleaning materials - CLOM with workpiece - Inventory shrinkage - single use operating materials - transport loss - trim loss |

## 5.5 Reflection

The Ishikawa exercise illustrates mechanisms for controlling the material waste quantity of a manufacturing system: through triggering or avoiding material consuming activities (or events), through affecting activity duration and through altering the quantity of material consumption per activity (or event).

The first two mechanisms indicates that the operating state modelling approach has some validity in modelling material waste consumption, as e.g. setups, working, and waiting or idling are activities. Each operating mode or transition could be modelled as a planned activity or an unplanned event causing a distinct material waste profile, e.g. cleaning materials for setup-state, defects and operating materials for work-state, only operating material consumption in idling.

The transitions between operating states and the turbulence that frequent transitions cause, particularly machine startups and shutdowns for setups, are inherent to modelling material consumption in the factory and cannot be neglected.

No evidence is found that would indicate the multitude of energy-profile-based operating states: blocked, waiting, energy-save, standby are different from one another in material consumption.

The third mechanism indicates that assuming constant lump-value or constant waste rate per operating state is too rough to model material waste quantities accurately. Ignoring the varying waste rates within an operating state greatly conceals the effects of e.g. employee qualification or product sequences on material consumption and thereby limits the number of improvement levers available to practitioners.

Therefore the following sections pursues an operating-state-based model of material efficiency in the factory with operating states that reflect distinct material consumption behaviors of work centers and the dynamic material waste rates that occur under a various process conditions.

# 6 A Model of Material Efficiency in Industrial Production

In the following section, a model for material efficiency in the industrial production is presented. The structure of this model is rooted in the types of material waste influencing factors and the mechanisms to control material waste, as discussed in 5.4. The model seeks to fulfill the specifications defined in 4.3.

First the material efficiency of the system (defined in 2.3.2) is expressed as a function of a production throughput, net material requirements, and total accumulated material waste for a given time period in Section 6.1. Since the net material requirement and the planned throughput of the system are fixed, material efficiency can only be increased through reducing the accumulated material waste at the operative level. Sections 6.2-6.3 break the aggregate material waste down into a machine-operating-state dependent and an operating-state independent portion, and then further into material waste occurring linked to specific operating states, activities, and unplanned events. Sections 6.4 and 6.5 describe the factors which exaggerate the amounts of material waste occurring for a given operating state, activity, or event.

The mechanisms to control material waste occurrence based on the structure of the model are described in Section 6.6.

## 6.1 Aggregate Material Waste and Material Efficiency

Factory material efficiency (ME) is defined as the ratio of material mass in finished goods produced in a period to the total material mass exiting the factory. Assuming the material efficiency is measured over an adequately long period, it can be expressed as a function of net material requirement per product, quantity of sold units, and the aggregate material waste, $M$ (Eq. 3):

$$ME = \frac{net\ material\ requirement\ \times\ quantity\ sold\ units}{M +\ net\ material\ requirement\ \times\ quantity\ sold\ units} \quad (3)$$

Since the net material requirements and the production volumes to satisfy market demand cannot be influenced by an operative decision maker, the only means to increase material efficiency is to reduce the aggregated material waste quantity.

The aggregate material waste quantity, $M,$ of the system can be modelled as the sum of all waste flows accumulating in a set of decentral material sinks over time, as shown in Eq. 4 for a set of q sinks.

$$M = \sum_{\mathrm{i}=0}^{q} M_{Sink} \tag{4}$$

Decentral material sinks represent a single workstation that transitions through a number of defined operating states, depending on controllable parameters and system constraints, resulting in noticeably different material waste rates. Activities occurring in the machine periphery, independent from the main machine module are also associated with distinctive waste rates. As an example, a cutting machine travels through a work state, setup state, idle state and error state, while an employee cleans the machine periphery independently. Therefore, the material waste of a sink consists of a machine module-attributed portion, and its periphery-attributed portion (Eq. 5).

$$M_{Sink} = M_{Module} + M_{Peripheral} \tag{5}$$

## 6.2 Machine Module Material Waste

Each operating state represents a steady-state activity (processing, idling, setup with a state-specific material waste rate and a typical material processing rate. Table 12 shows an overview of typical main module operating states. Work represents normal production at the specified process speed with an influence-factor dependent material consumption profile. All other operating states describe a form of downtime where no production occurs. Each downtime operating state occurs under a specific set of conditions and causes a distinct influence factor-dependent material consumption.

**Table 12: Generic operating states**

| *Operating State* | *Definition* |
|---|---|
| *Work (W)* | Resource in operation or online |
| *Idle (I)* | Resource waits for order information, material provision, material removal, employee qualifications |
| *Error (E)* | Interruption of operation, error, or breakdown |
| *Setup (S)* | Resource undergoes a change over or setup |
| *Planned maintenance (PM)* | The machine is offline and planned maintenance activities or housekeeping activities are occurring |
| *Off (O)* | Resource is out of operation, offline, or in standby |

Figure 38 provides an example for the case-specific logic that triggers each operating state. The machine module finds itself in an off-state outside of module-specific working hours. Preventative maintenance describes a state where the module is off, through material consumption is occurring through preventative maintenance or housekeeping activities. Material consumption varies based on indirect employee's qualification. Error occurs when the technical parameters of the processing module are not in order, causing a material consumption that is untypical for the module. A number of process disturbances, apart from technical process parameters, trigger an idle state, including "starving" (lack of material or an open order), "blocking" (hindered production due to a downstream backup or failed material removal system), and "waiting" (machine waiting for human input to proceed). In contrast to error, the idle state indicates the module is still in proper working order and therefore the accumulated material waste quantities are generally lower. Changing over from one product configuration to another may require a different machine configuration and necessitate a setup. Different materials are consumed during setup activities than other production activities (e.g. cleaning materials), and for that reason it must be modelled separately. The machine resumes the operating state "error" and "idle" in reaction to an unplanned sequence of events, therefore these states are called unplanned states in later sections. All other states are the results of a planned sequence of events.

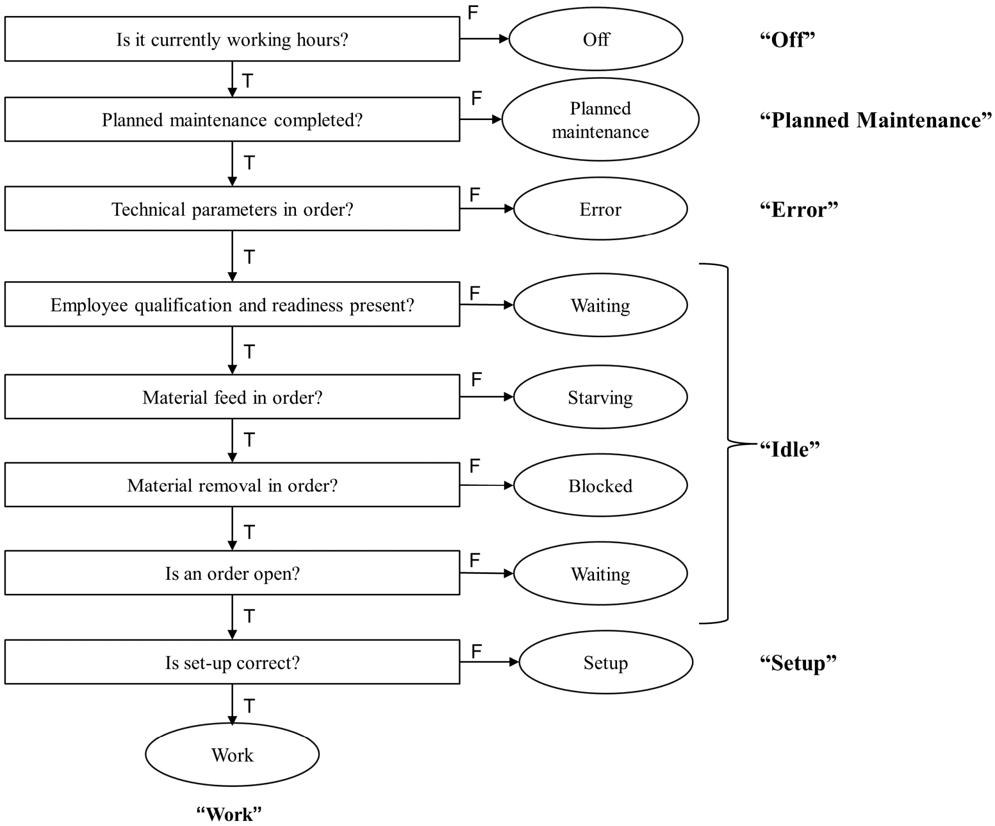



**Figure 38: Generic operating state logic**

When transitioning between operating states, discrete quantities of material waste may occur in a short time-period (e.g. startup losses). Therefore, the total material waste occurring at the machine module can be modelled as the sum of an integral of a state-dependent material waste rate and the sum of all material waste quantities attributed to material state transitions over a period as shown in Eq. 6.

$$M_{Module}(\mathrm{t}) = \int_{t_0}^{t} WR_{State}\,(\mathrm{t})dt \; + \sum_{\mathrm{i}=1}^{n} WQ_{Transition} \tag{6}$$

$M_{Module}(\mathrm{t})$: Stock representing the state-dependent and state-transition-dependent material waste accumulated at main module at current time, $t$

$t$: Current time

$t_0$: Initial time

WR $_{\mathrm{state}}$: state-dependent material waste rate of one sink [kg/min]

WQ $_{\mathrm{transition}}$: material waste quantity from operating state transitions [kg]

n: number of operating state transitions occurring between $t_0$ and $t$

## 6.3 Peripheral Material Waste

Peripheral activities, including cleaning and servicing the machine, may occur without resuming a planned maintenance mode. Therefore, to model the material waste causation of a material sink accurately, planned activities and unplanned events that do not directly correspond to a machine operating state are modelled as state-independent peripheral activities.

Peripheral activities may cause a fixed waste quantity per incident, or occur at a certain rate over the duration of the activity. Analogous to the machine-module waste, the peripheral activity waste consists of a duration-dependent and a duration-independent component, as shown in Eq. 7.

$$M_{Peripheral}(\mathrm{t}) = \sum_{\mathrm{i}=1}^{r} \int_{t_0}^{t} WR_{Peripheral}(t)\; dt \; + \sum_{\mathrm{i}=1}^{s} WQ_{Peripheral} \tag{7}$$

$M_{Peripheral}$: Activity-dependent material waste in the peripheral areas

$t$: Current time

$t_0$: Initial time

r: Number of simultaneous peripheral activity types

s:  Incidents of lump sum waste activities between t and $t_0$

WR $_{Peripheral}$: Material waste rate from each peripheral activity [kg/min] (= 0 when not activity not active)
WQ $_{Peripheral}$: Material waste quantity from lump-sum waste activities [kg]

Material waste rate vectors $WR_{state}(t)$ and $WR_{peripheral}(t)$ and material waste quantity vectors $WQ_{transition}(t)$ and $WQ_{peripheral}(t)$ represent a set of material waste rates and quantities for each material waste flow of homogeneous consistency and value. As shown in Eq. 8 and Eq. 9, the rates at which material waste occurs within an activity are functions of a number of controllable (flexible) and fixed parameters, y.

$$\overrightarrow{WR}(t, y_1 \dots y_p) = \begin{pmatrix} WR_1(t,\ y_1 \dots y_p) \\ WR_2(t,\ y_1 \dots y_p) \\ \vdots \\ WR_z(t, y_1 \dots y_p) \end{pmatrix} \tag{8}$$

$$\overrightarrow{WQ}(y_1 \dots y_p) = \begin{pmatrix} WQ_1(t,\ y_1 \dots y_p) \\ WQ_2(\ t, y_1 \dots y_p) \\ \vdots \\ WQ_z(t, y_1 \dots y_p) \end{pmatrix} \tag{9}$$

$\overrightarrow{WR}$: Material waste rate for one sink due to one operating mode or activity
$\overrightarrow{WQ}$: Material waste of one sink due to an operating state transition or activity
z: kind of material waste (e.g. rejects, chips, cutting fluids)
y: influencing parameters for material waste

## 6.4 Waste Amplifiers

The set of waste influencing parameters includes both parameters fixed through technological and market constraints, as well as parameters within the realm of factory management, including scheduling parameters, employee influence and local ambient conditions. Parameters that increase the amount of material waste above the minimum material waste quantity set by the technological constraints are designated “waste amplifiers”.
Material waste rates and the material waste quantities consist of a technology and product-variant specific baseline component and a “waste amplifier”

dependent component, as shown in Eq. 10 and 11. While causality can only be determined under controlled conditions, correlations between potential influence factors and the waste rates or waste quantities can be determined via linear regression. The external factor-dependent component of the material waste quantity is a function of multiple external waste amplifiers, $X$, and regression coefficients, $\beta$.

$$WR = X\beta + \varepsilon \tag{10}$$

$$WQ = X\beta + \varepsilon \tag{11}$$

In the following section, the in Section 6.6.4 identified waste amplifying factors, are described in detail. The definitions provided in Section 6.6.4 are summarized in Table 13.

**Table 13: Definition of waste amplifiers**

| Waste amplifier | Definition |
|---|---|
| Low commonality of successive product variants | Magnitude of differences in machine settings or required materials between successive product variants on a machine, that cause higher than average waste rates or quantities in production of the second variant. |
| Poor fit of machine assignment and product variant | The relative performance of a machine and product variant combination with respect to material waste in comparison to all other machine assignment combinations. Only applicable for work centers with multiple, interchangeable but not identical machines. |
| Poor machine and tool condition | The degree of machine and tool condition deterioration, in comparison with an ideally maintained machine or tool. |
| Long run length or short run length | The elapsed time in the work operating state without stoppage for readjustment compared to the average run lengths. This is considered a waste amplifier due to fatigue effects during long production runs or instability for a prolonged period after the immediate startup losses. |
| Low employee qualification and cost-consciousness | The qualification level and cost-consciousness of the employee based on the completion of formal trainings in comparison to the mean qualification level. |
| Unfavorable ambient conditions | The relative quality of air temperature, humidity, and contamination levels in the workstation area. Changes in air quality may explain differences in the material waste rates or material waste quantities for the same activities. |
| Long or short holding time | The elapsed time in storage allows for changes in material properties, leading to more or less material waste in subsequent activities. |
| Poor product mix quality | The degree to which product variants in a process batch complement each other, for instance, geometrically to reduce trim loss. |

### 6.4.1 Lack of Commonality between Successive Product Variants

Higher rates of material loss (particularly defects) occur when different product variants are successively produced under one or more of the following conditions:

- Residual material or traces of the previous material remain in the machine, leading to process defects in the subsequent lot: the cleanup in the setup procedure is not adequate to eliminate traces of the previous product, or no cleanup is carried out
- The risk of cross contamination requires an increased cleaning material consumption, and this risk is less so by other successive variant combinations

- Machine parameters are significantly different for the predecessor variant and the successor variant, leading to a longer instable startup period and large quantities of startup losses
- Bill of materials and the standard work procedures are fairly similar to the previous product variant, which increases the risk of mix-ups through employee error

While measurements (historical waste values) for a run of each variant combination could be taken, this would require the extraction of accurate data for $n \cdot (n-1)$ product variant combinations, a hefty task for most firms without automated waste monitoring.

Therefore, product commonality classes can be defined to estimate the material waste quantities without measuring every combination. Commonality classes (e.g. high commonality, low commonality) should describe to what extend product specification and process specifications can be handled similarly in an industrial environment. Estimating the product commonality of a pair of product variants requires both a review of process settings on the machine, as well as the product structure itself. If the changeover from one process variant on the machine to another necessitates different steps, activities, or settings, this may indicate that some variants have more commonalities with each other than with others.

In manual tasks (manual assembly or manual machine loading), the number of unique (non-common parts), and the number of deviations from a standard work procedure can be used as criteria.

Reviewing company setup matrices is a good starting point before interviewing process experts. Ideally, one to five levels of commonality can be defined, as shown in the example in Table 14.

**Table 14: Chocolate variant commonality levels for bar molding**

| *Commonality level* | *Required setup activities* | *Example variant sequence* |
|---|---|---|
| *Highest commonality* | No setup | Milk chocolate 100 g → Milk chocolate with almonds 100g |
| *High commonality* | Program change due to thickness | Milk chocolate 100 g→ Milk chocolate with almonds 100g |
| *Moderate commonality* | Flush charge, program change | Milk chocolate 100 g→ GMO free 100 g |
| *Low commonality* | Flush charge, tool change, program change | Dark chocolate 100 g→ Milk chocolate 50 g |
| *Lowest Commonality* | Intensive cleaning, flushing, tool change | Dark chocolate 100 g → white chocolate 50 g |

To validate if the defined commonality classes are defined correctly, material waste data from shop floor data acquisition can be compared with production schedules to investigate if the waste rates of the successor variants are higher than average following an uncommon predecessor variant lot. The effect should be examined for statistical significance using a regression analysis.

### 6.4.2 Fit of Machine Assignment

Similar to the lack of commonality of successive product variants, certain machines in a multiple machine park may yield better quality for each product variant. A scale of machine-variant-fit can be derived empirically. It is recommended to start by investigating the defect rates of similarly-aged machines producing the same, high runner product variant with the same tool so that machine and tool condition (considered as a separate waste amplifier) does not play a role.

### 6.4.3 Machine and Tool Condition

Technical literature indicates that heightened material waste may occur both at the beginning of equipment life, as well as at the end of equipment life (see Figure 23). Thus, advanced age of tool and machine components may be modelled as a waste amplifier. The performance of technology based on age, however, is dependent on the loading of the equipment and the diligence of preventative maintenance activities. Therefore, a scale must be defined for each set of similar technologies.

### 6.4.4 Length of Production Run

As discussed in 5.1.1.5, technical literature supports that short production runs lessen the material waste occurring during a production run, as they prevent the machine from destabilizing over time for some processes, while for others, lingering startup instability increases waste quantities for a period after machine setup. It is assumed that the length of the production run influences waste quantities in not only the immediate work-state, but also subsequent setup activities and clean-up activities. Therefore the length of other activities (i.e. setup times) are not considered waste amplifiers. The relationship between the predictor, elapsed time in operating state, and material waste rate can be determined over a regression analysis between material waste data and production schedules. Unlike product variant commonality and machine fit, lot size data is readily available for comparison with waste data, without the need for classification or ranking.

### 6.4.5 Employee Qualification and Cost-Consciousness

Employee qualification, attentiveness, and motivation may influence the amount of material waste that occurs in a given operating state (e.g. defect rate when processing workpieces) or for a discrete activity (e.g. cleaning waste quantities and excessive paint dispensing). Additionally, employee qualification can influence the duration of undesired operating states (e.g. idling) through human error and lack of troubleshooting skills. Therefore, employee qualification is represented as a waste amplifier for material waste quantities and amounts, as well as a parameter for determining if a machine can maintain a workpiece processing work state.

Employee qualification data is readily available in the most companies as a skills-matrix, usually with 3-4 qualification levels corresponding to the scope of the employee's capabilities. Through a regression analysis of shop floor data collection, the strength of the correlation between employee qualification and material waste accumulation can be determined.

### 6.4.6 Unsuitable Ambient Conditions

Without process enclosures, the ambient conditions of the factory building may directly affect material waste accumulation. However, the impact of these ambient conditions on the material waste quantities and material waste rates of activities needs to be determined on a case-by-case basis. Some temperature ranges and humidity levels may be favorable for some activities, while others cause considerably more waste at the same levels. Correlations between process waste, temperatures, and humidity can be determined with regression analysis; however, depending on the waste form, a reverse-causal relationship may be present. The accumulation of material waste, especially fluid wastes (e.g. cutting fluid) may directly affect local temperatures and humidity levels. Since regression analysis can only determine correlations between variables, not causality, a design of experiments is necessary to determine if the waste is driving changes in ambient conditions, or the ambient conditions are driving material waste, or both.

### 6.4.7 Long Holding Times

As discussed in 5.1.2, holding times play a crucial role in the material waste rates and quantities of inventory deterioration. Additionally too long or too short holding periods may lead to process defects or excessive material consumption through machine parameter deviations.

### 6.4.8 Product Mix

Classically addressed in trim loss literature (see Section 5.1.4.4), advantageous product mixes may also increase defect quantities in some multi-product batch processes (e.g. tempering), due to the temperature distribution in the oven. Therefore product mix is investigated in all manufacturing processes, where a set of product variants is processed simultaneously.

## 6.5 Interdependencies between Material Sinks

Unless material sinks are operating in complete isolation, with excessive buffering between successive processes and operating spatially distanced from one another, interdependencies are unavoidable. Material sinks are linked with one another through logistical relationships as suppliers or customers of other material sinks. Thereby an interdependency via logistical linkage exists, and certain planned or unplanned activities may be triggered at one material sink due to an activity or a change in operating states (e.g. idling state caused by a downstream system error state). The set of material sinks corresponds to the organizational form of the factory (e.g. line structure or job shop). In Figure 39, two logistically linked material sinks are presented in the foreground. The linkage of other material sinks may be attributed to their spatial proximity to one another. For instance, changes in ambient conditions may be attributed to the outputs of a material sink (waste material, noise vibrations), initiating technical errors or increased material waste flow rates in a neighboring process. This relationship is demonstrated between the process in the foreground and the process in the background in Figure 39.

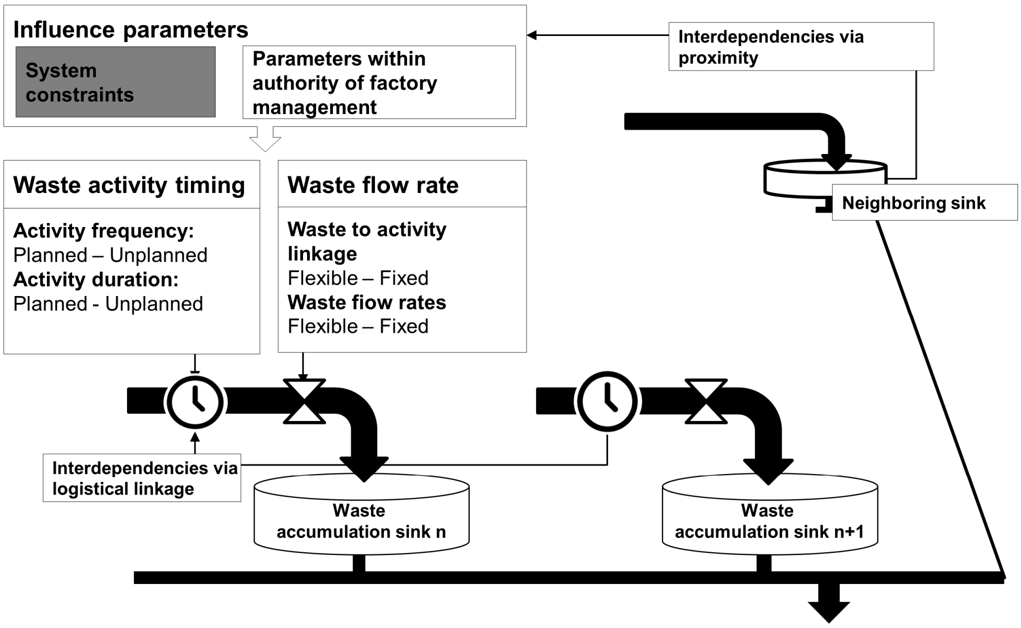



**Figure 39: Controlling material consumption in manufacturing systems**

## 6.6 Control Mechanisms in Operative Management

The in Section 5.1 described influence factors affect the amount of waste that occurs in the system through different mechanisms. Activity-triggering factors may determine the frequency of material-waste-causing activities or the likelihood of an unplanned material-waste-causing event. Other factors influence the duration of planned activities or unplanned events, therefore increasing the material waste for activity-duration dependent waste forms. A third set of influence factors determine whether a material waste form is coupled with an activity or event, a linkage that may be flexible for some waste forms. The final set of influence parameters increase the material waste quantities or the material waste rates for a given activity or event. Each of these four sets of influence factors are described in the following sections.

Reviewing equations 1-6 reveals four levers that cumulatively determine the total quantity of accumulated waste in a manufacturing system, shown as the clock and valve in Figure 39 and summarized in Figure 40.

**1. Frequency of material waste triggering activities**: As discussed in 5.1, material waste forms are linked with activities or events. Examples include cleaning materials (cleaning activities), process defects (workpiece processing), and trim loss (cutting stock material). If no material-waste-causing activities, operating states or transitions occur, the total waste accumulation is zero. This lever corresponds to the “Prevention” strategy of the recycling hierarchy. However since some activities are critical for the performance of the factory, particularly workpiece processing (ensuring production volumes) it is impossible to fully avoid all activities without endangering the performance of the factory. Selectively reducing the activity frequency of non-value adding activities presents potential for waste reduction, though trade-offs in manufacturing performance may occur, or other waste-causing activities may be triggered more frequently.

2. **Duration of material waste activities or operating states:** Minimizing the duration of certain machine operating states and limiting the duration of waste-causing activities presents another lever to minimize material waste. This only applies to activities where the consumption is proportional to the duration (not fixed quantities per incident). For instance, paint losses in the work-state of a paint-shop, which can be modeled as a function of time, and occurs regardless of the presence of a workpiece. In this case, shortening the work-state periods of the machine only to when a workpiece is inside and resuming a lower-waste state when no workpiece is present would improve the material efficiency. This is a form of the “minimization strategy” of the recycling hierarchy.

3. **Linkage of material waste forms with activities:** In contrast with the first two control mechanisms, the third focuses on how much waste occurs per activity, not when and for how long the activity occurs. Certain material waste forms can be decoupled from their triggering activities using a combination of technical and organizational measures.

4. **Material waste rates and quantities:** If the material loss form cannot be fully decoupled from the trigger activity, minimization strategies can be used

to reduce the base-line activity specific consumption, as well as control influence parameters or lessen their effect on material waste rates. This includes controlling cross-process influences over ambient conditions.

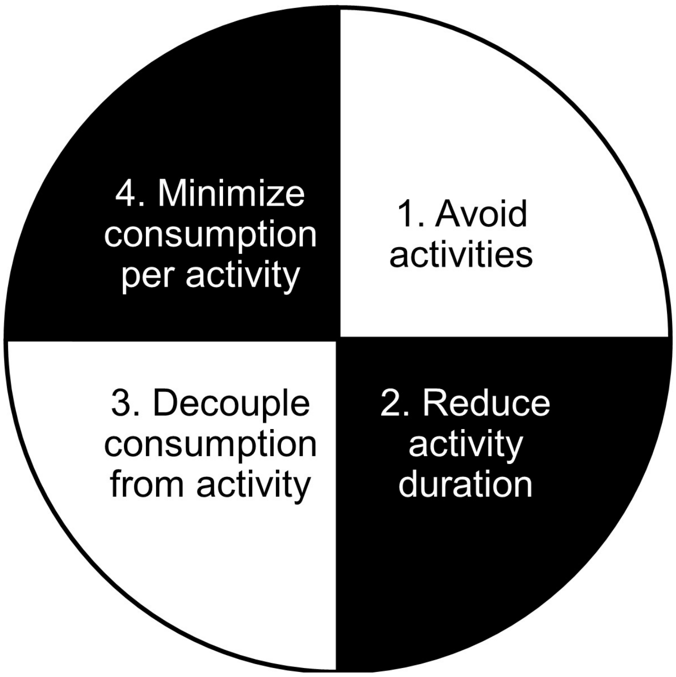



**Figure 40: Material efficiency improvement mechanisms**

In the following subsections, 6.6.1-6.6 analyses the overall effectiveness of these strategies by examining the concrete tactics that manufacturers could use to follow these strategies. The tactics were consolidated from references in technical literature as well as interviews with process experts in manufacturing settings. Two main aspects were considered in the evaluation, firstly: *how much material waste does this tactic target?* This aspect is expressed as **scope of material savings** where tactics addressing large volume materials, high cost materials, and multiple materials received high rankings, in accordance with the evaluation scale described in Table 15.

Secondly, the parameter, **feasibility within operative decision-making**, evaluates the positioning of the tactic within the authority of an operative decision maker. As reflected in Table 15, the ability of operative decision makers to execute the tactics may vary from case to case, and therefore the evaluation scale is based on a set of reference cases. The case-specific character is often based on the current equipment available in the manufacturing facility, e.g. a segmentation of the production is coupled with investment for a facility with a single manufacturing line, while for a facility with multiple lines it is not. The overall effectiveness of each strategy is examined in Section 6.6.5. The total score for the effectiveness of each strategy results from the average of the individual activity evaluations.

**Table 15: Criteria for strategy evaluation**

| Parameters in Tables 16 -19 | Rating | Criteria (valid if at least one criteria fulfilled) |
|---|---|---|
| Scope of material savings | ● | > 4 material waste forms affected<br>> 40% total material waste cost linked to this activity in reference cases |
| | ◕ | > 3 material waste forms affected<br>> 20% total material waste cost linked to this activity in reference cases |
| | ◐ | > 2 material waste forms affected<br>> 10% total material waste cost linked to this activity in reference cases |
| | ◔ | > 5% total material waste cost linked to this activity in reference cases |
| | ○ | < 5% total material waste cost linked to this activity in reference cases |
| Feasibility within operative decision-making | ● | Strategy is within the authority of operative decision makers under all circumstances in reference cases |
| | ◕ | Strategy is within the authority of operative decision makers in most cases in reference cases |
| | ◐ | Strategy is within the authority of operative decision makers in some cases in reference cases |
| | ◔ | Strategy is within the authority only In exceptional cases |
| | ○ | Beyond the authority |

### 6.6.1 Occurrence of an Planned Activity or Unplanned Event

Limiting the occurrence and duration of known material-waste-causing activities or operating states presents one lever to reduce material waste.

The feasibility of limiting the occurrence frequency of material waste activities and the extent to which factory management has authority to do so needs to be examined on a class-by-class basis. For that reason, both planned activities, namely activities that are a result of proactive operative decision-making, and unplanned activities, which occur due to an unintentional change in system parameters or reactive efforts to counteract these activities or operating states, are examined in the following section.

**The piece-processing or machine batch interval (planned activity, work state):** Waste occurring when processing a single workpiece in a machine or in a fixed machine batch size can be is described as occurring every piece interval or batch interval respectively. Under ideal conditions, the accumulated material waste is proportional to the production volume. The piece interval is assumed rigid, in that, it cannot be changed by changing the total production volume (throughput) of the factory, and it is beyond the authority of OM to refuse production orders. However, by avoiding overproduction, piece-processing activities can also be avoided. Similarly, by avoiding defects, repeating the piece processing to replace or repair parts is avoided.

**The stock-material processing interval (planned activity, work state):** Material waste in the stock-material cycle, describes material waste occurring with every raw material unit that is processed in the factory, and regardless of the number of parts that are ordered. Examples include the ends of coils or trim loss from the cutting of stock-sheets. Depending on the cutting technology and process specifications, it may be possible to make the occurrence of trim loss less frequent by using larger stock units (e.g. longer coils).

**Setup interval:** Assuming customer orders can be filled from a finished goods warehouse, warehouse costs and capital lock-up are negligible, and the product is not subject to deterioration, setups on multiproduct machines can be performed at low frequencies by bundling multiple orders to large lots. Waste triggered by every setup cycle describes material waste occurring before, during or after a setup activity. Examples include startup and shutoff losses, discarded auxiliary material, and cleaning solvent consumption.

**Maintenance intervals (planned activity, preventative maintenance state):** Maintenance cycle waste describes the materials that are used by maintenance staff during routine maintenance activities, including lubricants and cleaning solvents, as well as the shutdown losses (process defects) occurring when the machine is prepared for maintenance. Bundling the maintenance activities and performing all maintenance jobs for one workstation at once reduces the frequency of maintenance-related shutdowns.

**Transport intervals (planned activity, peripheral module):** Waste linked with the transport-cycle describes the lump-sum waste with the transport of a set of parts, which may not be proportional to the number of pieces or batches produced. Loading more pieces on transport vehicles would reduce the frequency of transport activities. Depending on the distances travelled and the organization type, multiple handling activities may occur between two successive workstations. Reducing these activities can be achieved through organizational (e.g. suppliers deliver directly to shop floor) and technological changes (e.g. direct conveyors to point of use).

**Destructive testing intervals (planned activity, peripheral module)**: Material loss linked with the test cycle describes the material destroyed in destructive testing. As destructive testing is assumed to be a strategic decision, this form of material loss is fixed for a given production system. Management can merely avoid unnecessary testing by limiting overproduction.

**Housekeeping intervals (planned activity, peripheral module):** The housekeeping cycle describes waste that occurs when tidying up a work station as a part of a daily housekeeping routine, and therefore may consist of cleaning solvents and any materials that are to be discarded at the end of the shift (open paint containers). Cleaning activities can be avoided by preventing waste from occurring e.g. through closing doors and following handling procedures to prevent spills, as well as encouraging cleaning only in certain times, when enough dirt has collected to warrant the use of cleaning materials.

**Machine breakdown interval (unplanned event, error state):** The machine breakdown cycle describes how frequently the main process module falls into an error state, causing out of range process parameters and causing material waste to occur. Mean time to failure (MTTF) is a key performance indicator describing the error-free runtime (time in work-state) that can be achieved before entering an error state. A number of maintenance strategies can be utilized to lengthen the mean time to failure, including more frequent and extensive preventative maintenance activities and lessened machine loading, though constraints of the machine system, including its age and the current production load, prevent measurable gains.

**Machine idling intervals (unplanned event, idle state):** As shown in Figure 38, machine idling occurs for a variety of reasons. In linked workstations working in one-piece flow, short “starved” or “blocked” periods can occur in every tact. Idling due to starving or blocking can be prevented by ensuring a minimum buffer level and not limiting the maximum level, respectively. Preventative maintenance for machine feeding technology or awareness training for employees can help prevent starving conditions. Lack of orders can be remedied by ensuring a minimum number of orders are available in the queue.

**Material aging (unplanned activity, peripheral module):** Material aging describes instances of exceeding the material lifetime within a manufacturing facility. Instances of material aging in the factory occur less frequently if employees are adequately trained to maintain cutting-fluid systems, and the influence of external factors, e.g. contaminants, is limited. Limiting the holding time of deteriorating or fashion goods reduces the risk of waste.

**Material mishandling (unplanned activity, peripheral module):** Inventory deterioration that can be directly linked with a single event (unlike material aging), can be prevented through staffing and qualifying employees, enforcing standard work procedures, and limiting the transport or storage of goods under suboptimal conditions.

#### 6.6.1.1 Potential for Limiting Waste-Causing Activities in the Factory

Based on the evaluation criteria described in 6.6, the perceived potential for activity avoidance shown in Table 16, along with the waste forms that generally are triggered by the occurrence of these activities or operating states. While avoiding overproduction is within the authority of factory management, reducing the number of workpieces processed below customer demand is not possible, therefore the potential, especially in contract manufacturing is low. Processing machine batches can be limited by making sure the batch container (e.g. a paint shop rack) is full and avoiding over production of batches; however, undercutting the minimum number of batches necessary to produce the customer demand may not occur. Therefore the potential for avoidance is also estimated to be low.

The setup interval presents comparatively high potential to reduce material waste, though potential trade off with inventory deterioration and sluggishness of the system cannot be disregarded. Manufacturers are free in setting maintenance intervals, though undercutting a lower limit leads to increased risk of breakdown and quality defects. While a minimum number of transport activities are required, multiple touches regularly occur between value-adding processes. Therefore, avoiding transport activities presents an opportunity for many manufacturers. Similarly avoiding idling states presents an opportunity within the authority of OM, because idling can be through increasing inventory levels in many cases. The likelihood of inventory deterioration can be avoided by using a fitting dispatch policy (FIFO or LIFO), reducing inventory levels and consequentially the material holding time.

Comparing the potential to avoid material-waste-causing activities with the material waste intensity of these activities (based on the number of waste forms, the certainty of their occurrence, and typical quantities), setups present the most opportunity for improvement. Setups are one of the most waste-producing processes in injection molding and paint shop processes, and one of the few intervals defined by decision-makers in the factory. The occurrence of destructive testing is an example outside of the authority of operative decision makers.

**Table 16: Waste prevention through activity occurrence avoidance**

| | Tactics | Addressed activity and linked waste forms | Scope of material savings | Feasibility within operative decision-making |
|---|---|---|---|---|
| Planned activity intervals | **Avoid workpiece processing:**<br>- Defect avoidance<br>- Avoiding overproduction<br>- Better utilization of batch containers (e.g. paint racks) | Workpiece processing or batch processing: defects, trim loss, chips, byproducts, aux., cutting fluids, cleaning materials, lubricants | ◐ | ◔ |
| | **Avoid material unit replenishment:**<br>- Larger stock units (e.g. longer coils) | Material unit replenishment: trim loss | ◔ | ◔ |
| | **Avoid setups:**<br>- Bundling orders/ larger lots | Setups: defects, cleaners, auxiliary materials | ◐ | ◕ |
| | Avoid maintenance activities:<br>- Bundling activities | Maintenance: lubricants | ◔ | ◐ |
| | Avoiding storage:<br>- Immediately processing/ inventory reduction | Storage: intermediate packaging | ◔ | ◐ |
| | Avoiding transport:<br>- Loading more pieces on vehicles<br>- Avoiding excessive handling | Transport: transport loss | ◔ | ◐ |
| | Avoiding destructive testing:<br>- Avoiding overproduction | Destructive testing: defects (startup/ shut-off) | ● | ◔ |
| | Avoiding housekeeping:<br>- Prevent spills and messes<br>- Clean only at management designated times | Housekeeping: cleaning materials, auxiliary materials | ◐ | ◕ |
| Unplanned activity intervals | Avoiding machine breakdowns:<br>- Preventative maintenance<br>- Reduced loading | Machine breakdown: defects (startup/shut-off) | ◐ | ◐ |
| | Avoiding machine idling:<br>- Higher inventory levels (decoupling)<br>- Preventative maintenance on feeder technologies<br>- Employee awareness training | Machine idling: defects (startup/shut-off) | ◔ | ● |
| | Avoiding material aging:<br>- Limit holding times<br>- Employee qualification | Material aging: inventory shrinkage, closed loop operating materials, auxiliary materials | ◐ | ◐ |
| | Avoiding mishandling:<br>- Employee awareness and safety training | Mishandling: inventory shrinkage | ● | ◐ |
| ***Total score*** | | | ◐ | ◐ |

### 6.6.2 Duration of Planned Activities and Unplanned Events

If the quantity of material waste is associated with a constant machine state, and not a discrete event, the material waste quantity may be minimized by shortening the state duration.

**Workpiece or batch processing duration:** The duration of workpiece processing or batching processing is determined by the processing speed. Assuming the material waste accumulation rates are the same, switching to a machine with a faster processing time reduces processing duration. However in the case of process batches, increasing the utilization of batch units presents a further opportunity to shorten the batch processing time.

**Idling duration:** The ability to shorten the duration of idling states depends on the cause of the idling state. If the machine is starved, hence has no workpiece in process, technical errors in the machine feed, an inattentive employee, a technical error or quality defects in an upstream process may be to blame. In the case of technical errors on the machine feed, shortening the time to repair may be achieved by increasing maintenance resources, shortening the distances for maintenance personnel to travel, or cross-training machine operators to troubleshoot feeding equipment. In the case of a manual machine feed, the idling can be reduced by ensuring the employee is present, by ensuring a springer is available to cover absences for bathroom breaks, increasing the number of employees in a multiple machine operation system, or reducing the secondary activities required of operators. If the failed manual machine feed can be attributed to employee inattentiveness, both disciplinary actions as well as cost and environmental awareness trainings may be utilized. Blocked conditions are similarly caused by an error in the material removal system, inattentive employees, or technical errors in connected downstream processes. The duration of blocked conditions can be shortened by reducing the time to repair for errors in the material removal system and downstream processes. Similar to starved conditions, blockages due to piece-jams can easily be alleviated if an attentive employee is always present, available, and motivated.

Idling due to missing production jobs can be shortened by ensuring that procedures are in place to shut down the machine after exceeding a maximum idle period or allowing employees to shift queuing jobs to an idle, but perhaps less preferred machine quickly.

**Machine breakdown duration:** The period a machine module remains in an error state following an unexpected disturbance can be minimized by increasing maintenance resources, shortening the distances for maintenance personnel to travel, or cross-training machine operators to troubleshoot feeding equipment. The repair and troubleshooting procedures themselves can also be reduced using process reengineering techniques.

**Setup duration and planned maintenance activity duration:** Using SMED the duration of setup activities can be reduced. One approach is through performing preparation activities while the machine is still running or post-setup activities after the machine is returned to working order. Other approaches include better housekeeping and standardizing work procedures. However, it should be noted that many setup-linked material waste forms occur at fixed quantities per setup (e.g. cleaning supplies, startup losses), and are not activity-duration dependent. Similarly, planned maintenance activities are generally not duration-dependent.

#### 6.6.2.1 Potential for Shortening Waste-Causing Activity Duration in the Factory

The controllability of activity duration, for activities where waste accumulation occurs as a function of activity duration, is demonstrated in Table 17 (see evaluation criteria in Section 6.6). Activity duration of all non-productive activities is easy to influence utilizing a number of strategies. However, the potential associated with shortening activities should not be overestimated. Most material waste forms are not a direct function of the time spent in a machine operating state. The losses of material associated with the operating states of error, idle, setup, and planned maintenance are a result of initiating the operating mode (i.e. the transition to the operating mode), not the duration, an inherent difference from energy and utility consumption.

**Table 17: Waste minimization through activity duration adjustment**

| | Tactics | Addressed activity and linked waste forms | Scope of material savings | Feasibility within operative decision-making |
|---|---|---|---|---|
| Planned activity intervals | Shorten processing duration<br>- Assignment to the fastest machine | Workpiece processing: auxiliary / operating materials | ◔ | ◔ |
| | Shorten setup duration<br>- SMED | Setup: auxiliary / operating materials | ◔ | ◕ |
| | Shorten planned maintenance duration<br>- Process optimization | Planned maintenance: auxiliary / operating materials | ◔ | ◕ |
| Unplanned activity intervals | Shorten machine breakdown duration<br>- Mean time to repair reduction | Machine breakdown: auxiliary / operating materials, defects | ◔ | ◕ |
| | Shorten machine idling duration<br>- Mean time to repair reduction for feeder and removal technology<br>- Employee presence and empowerment | Machine idling: auxiliary / operating materials, defects | ◔ | ◕ |
| ***Total score*** | | | ◔ | ◐ |

### 6.6.3 Coupling Activities with Material Consumption

Depending on the waste form, it may be possible to delink the material waste form from the triggering activity.

**Adjusting process specifications:** Depending on the case-specific limits of operative decision-making, it may be possible to forgo the use of certain operating materials completely. Examples include changing cutting conditions to use minimal-lubrication machining or dry-processing, thereby eliminating cutting fluid losses.

**Turning off unneeded machine components:** manually or automatically turning off unneeded machine modules when the machine is starved, blocked, or disrupted presents an opportunity to delink auxiliary and operating material consumption from inactive operating states. Examples include deactivating paint pistols when no workpieces are detected on a paint shop rack. However, the required capital investment may not fall under the authority of operative decision-makers.

**Workpiece storage:** Similarly, management may be able to stage parts without intermediate packaging if holding times are brief and ambient conditions are controlled.

#### 6.6.3.1 Potential for Limiting Waste through Delinkage from Activities

With the exception of intermediate packaging, forgoing material consumption or decoupling it from activities is not a feasible lever to improve material efficiency for operative decision makers. An evaluation of the above-mentioned decoupling strategies is presented in Table 18, using the evaluation criteria described in Section 6.6.

**Table 18: Potential for waste prevention via consumption delinkage**

| | Tactics | Addressed activity and linked waste forms | Scope of material savings | Feasibility within operative decision-making |
|---|---|---|---|---|
| Planned activity | Delinking from workpiece processing: Forgoing consumption by adjusting process specifications (e.g. dry-machining) | Workpiece processing: Operating materials (e.g. cutting fluids, intermediate packaging) | ◔ | ◔ |
| Planned activity | Delinking waste from storage: Forgoing consumption through organizational changes (e.g. intermediate packaging) | Storage : Intermediate packaging | ◔ | ◐ |
| Unplanned activity | Delinking waste from machine idling: Turning off unneeded, waste-causing modules in inactive periods | Machine idling: Auxiliary / operating materials, defects | ◔ | ◔ |
| ***Total score*** | | | ◔ | ◔ |

### 6.6.4 Decreasing the Material Waste per Activity

Therefore three possible strategies result to minimize the material quantity per activity or per time unit:

I. Reducing the sensitivity to waste amplifiers (minimize $\beta$)

II. Controlling the values of waste amplifiers (minimize X)

III. Reduce the technology and product variant specific constant (minimize $\varepsilon$)

Strategy III is very limited within the constraints of an existing production system without changes to product structure and therefore is not pursued further. The potential for lowering the activity-specific consumption of operating materials is discussed as a delinking strategy in Section 6.6.3.

#### 6.6.4.1 Potential for Desensitizing the System to Waste Amplifiers

**Lack of successive product variant commonality:** to desensitize the manufacturing process to the lingering effects of the last product variant different measures can be taken based on the type of discommonality between the product variants. For example if residues left in the machine from the predecessor variant can contaminate the new product, technical measures may be taken to lessen the buildup of residues in a machine, including equipment coatings. Alternatively, some machines may be cleaned without using cleaning materials, though this generally requires large quantities of hot water or manual scrubbing, potentially adding to the setup duration.

For product variants requiring different process settings, e.g. temperature, accelerating the process stabilization rate after a setup generally requires equipment modification (e.g. an additional heat source) and machining reprogramming investments. Therefore, it is considered unfeasible for an operative decision maker.

If the product sequence sensitivity is related to employee confusion, Poka-yoke mechanisms in the workstation can reduce the likelihood of employee mix-ups. Examples include bin covers to reduce the risk of employees grasping incorrect screws. Further poka-yoke measures can be taken in product design to prevent errors in the workflow, though outside the scope of operative decision-making. Employee training and sensitization to the product differences can also decrease incorrect builds.

**Unsuitability of machine/product variant combination**: based on the relative definition of this waste amplifier, i.e. if unsuitability has no effect, the unsuitability is non-existent. Therefore for unsuitability, only reducing the magnitude of unsuitability, controlling its value, remedies the increased material waste rates.

**Advanced equipment age**: preventative maintenance and repairs can effectively improve the condition of older equipment, and therefore lessen the system's sensitivity to the machine's age, without changing the make year of equipment.

**Large lot size/long production runs**: technical measures, including process monitoring, can be taken to ensure the consistency of machine parameters over a production run, making adjustments when needed. Process monitoring could be executed in an automated system or manually, allowing larger lots to be run without increased waste.

**Low employee qualification**: increased process automation can lessen the sensitivity of the system to less qualified employees. However, process automation requires investment and is not within the authority of an operative decision maker.

**Out-of-range ambient conditions**: Physically enclosing processes shields the effects of out-of-range ambient conditions. Enclosures, however, require capital investment and therefore exceed the authority of an operative decision maker.

**Too long or too short holding times:** material properties are subject to change over time. In some cases this is desired, in others less so. If material waste through inventory deterioration is modelled at the point of discovery, the likelihood of its can be modelled as a function of holding time.

Overall desensitization of the factory system to the identified waste amplifiers without capital investment is limited, as shown in Table 19 (see evaluation criteria in Section 6.6). Nevertheless, operative decision makers can utilize organizational instruments.

**Table 19: Waste minimization through desensitizing the system to waste amplifiers**

| **Tactics** | **Addressed activity and linked waste forms** | **Scope of material savings** | **Feasibility within operative decision-making** |
|---|---|---|---|
| Desensitizing to lack of successive product variant commonality:<br>Residue prevention<br>- barrier mechanisms (coatings)<br>- manual / material-waste free cleaning | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners | ◐ | ◔ |
| Desensitizing to lack of successive product variant commonality:<br>Accelerating process stabilization<br>- technical measures | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners | ◐ | ◔ |
| Desensitizing to lack of successive product variant commonality:<br>Preventing employee confusion<br>- poka-yoke mechanisms<br>- training | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners | ◐ | ◕ |
| Desensitizing to advanced equipment age:<br>Preventative maintenance activities | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners | ◐ | ◕ |
| Desensitizing to large lot sizes:<br>Process monitoring and parameter adjustment | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners | ◐ | ◐ |
| Desensitizing to low employee qualification:<br>Increase process automation | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Material replenishment: trim loss | ◐ | ◔ |
| Desensitizing to out-of-range ambient conditions:<br>Enclose processes | Workpiece or batch processing: defects<br>- Startups: startup losses<br>- Cleaning: cleaners<br>- Transport: transport loss | ◐ | ◔ |
| ***Total score*** | | ◐ | ◐ |

### 6.6.4.2 Potential for Controlling Waste Amplifiers

**Lack of product variant commonality**: To increase product variant commonality of any two successive product variants, there are two approaches which can be taken: either make every product variant physically more similar, in both product design and process specifications or alternatively only run product variants successively that possess a minimum level of commonality.

Products can be made more similar by changing the color, material, shape, and required manufacturing processes. Modularity enables increased commonality in upstream fabrication processes, by using the same base modules, though downstream final assembly may lead to an increased risk of mix-ups, if all unique product characteristics are encapsulated. However, making any design changes is outside the limits of operative decision-making, and therefore will not be further considered.

Campaign-building bundles product variants with commonality together to larger batches or “campaigns”. The shift to another campaign and the corresponding instance of low commonality occurs less frequently.

Another approach to limit the instances of low commonality in a machine park with multiple, interchangeable machines is to assign parts with low commonality to different machines, thereby segmenting the production.

**Unsuitability of machine/product variant combination**: Assuming two mutually exclusive groups of suitability, product segmentation can be carried out, so that only suitable products are assigned to each machine type. These are also called “dedicated” machines. If one group of product variants is suitable for production on all machines, but other product variants are only suitable for one machine type, prioritization of the less-universally suitable product variant orders can reduce the likelihood of an unsuitable product variant – machine pairing.

Alternatively, technical measures can be taken to make all machines universally suitable and therefore interchangeable, or product design measures can make all products suitable for production on any machines. Both approaches are, however, outside of the scope of this work.

**Advanced equipment age**: Avoiding advanced equipment age on the utilized machines can be avoided through two mechanisms. One is to eliminate all machines above a certain age limit, and therefore requires an immediate capital investment for most firms, as well as increased machining costs due to shorter depreciation periods. The second mechanism is to prioritize the use of newer machines and use only the old machines under exceptional conditions (i.e. high season). This is only effective when factories have a surplus of machine capacity.

**Large lot size/long production runs**: Avoiding long production runs or large lot sizes can be realized through changes to the production plan, i.e. making short stops for parameter readjustment or to setup for another product variant. However, this is only an option for facilities with a machine capacity surplus that can afford to perform more frequent setups.

**Low employee qualification**: Increasing employee qualification is easily implemented as long as employee retention rates are high in the company, and adequate resources are provided for training.

**Out-of-range ambient conditions**: Ambient conditions can be regulated by controlling conditions within the production hall. This includes installing and maintaining HVAC systems, dehumidifiers, and condition monitoring systems. Furthermore, advantageous ambient conditions can be maintained by containing local changes in ambient conditions (i.e. cutting fluid mist containment). Both approaches require capital investment.

Manufacturers can also avoid exceeding acceptable ambient condition levels by timing the production of only robust product variants on high temperature, high-humidity days.

**Table 20: Waste minimization through controlling waste amplifiers**

| Tactics | Addressed activity and linked waste forms | Scope of material savings | Feasibility within operative decision-making |
|---|---|---|---|
| Controlling successive product variant commonality:<br>a. Product standardization, modularization<br>b. Campaigns/ bundling batches with high commonality<br>c. Assigning uncommon product variants to opposing machines | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners | ◐<br>◐<br>◐ | ○<br>◕<br>◕ |
| Controlling unsuitability of machine / product variant combination:<br>a. Assigning product variants only to the most suitable machine<br>b. Product simplification<br>c. Machine universality | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Stock unit replenishment: trim loss | ◐<br>◐<br>◐ | ◕<br>○<br>○ |
| Controlling advanced equipment age:<br>a. Investment in new machines<br>b. Prioritize utilization of newer machines | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Stock unit replenishment: trim loss | ◐ | ○ |
| Controlling large lot sizes:<br>Run small lots | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Stock unit replenishment: trim loss | ◐ | ◐ |
| Controlling low employee qualification:<br>Train employees | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Stock unit replenishment: trim loss | ◐ | ◕ |
| Controlling ambient conditions:<br>a. Controlling and containing ambient conditions<br>b. Producing only robust-product variants in periods of undesirable ambient conditions | - Processing defects<br>- Startups losses<br>- Cleaning: cleaners<br>- Transport: transport loss<br>- Stock unit replenishment: trim loss | ◐<br>◐ | ○<br>◐ |
| ***Total score*** | | ◐ | ◐ |

Table 20 presents an evaluation of the tactics for controlling the values of the waste amplifiers using the evaluation criteria from Section 6.6. While technical measures present a very effective method to control the values of waste-amplifying factors, machine segmentation, campaign building, order prioritization, and the timing of order processing hold potential to reduce material waste.

### 6.6.5 Summary of Control Mechanisms

Following the evaluation of the individual material efficiency tactics, Figure 41 displays how far-reaching and how feasible the control mechanisms are for an operative decision maker.

The longest list of tactics was generated for the control mechanism, *activity avoidance*, due to the broad scope of activities (not just long-duration activities) as well as the straightforward nature, which quickly yielded tactics in expert interviews. The feasibility of avoiding an activity in a manufacturing system heavily rides on the nature of the activity, because superfluous non-value added activities could easily be avoided through simple measures or bundled to be performed as a single activity. The strategy reaches its limit when the material waste intensive activity is the processing of a single piece. Therefore this approach can be seen as a ‘beginner’ step for a manufacturing system rich with non-value added activities causing many unnecessary operating state transitions, while a well-scheduled facility will see little improvement through this strategy. Of the set of non-value adding activities, the largest material waste scope is observed in activities causing machine startups and shutdowns (frequent variant changes and maintenance activities). Large improvements in material efficiency can be reached through the bundling on activities to avoid operating state transitions (activity avoidance), though this approach conflicts with the principles of lean production: to produce small lot sizes in tune with customer demand.

Activity shortening, unlike activity avoidance, is only applicable to duration-dependent material waste quantities, yielding a smaller set of tactics. While few activities are linked with a duration-dependent waste quantity, the tactics were rated as highly feasible, since duration is primarily dictated by organizational factors (e.g. the duration of a setup or maintenance activities) rather than technologies. The duration-dependent quantities of material loss in reference cases consisted of operating and auxiliary materials, whose value and waste quantity (in kg) was significantly lower than other waste forms in the system (e.g. defects), therefore the scope of the materials is limited. However, the nature of this approach is aligned with lean production: long non-value added activities waste employee time and waste materials.

The *waste delinkage* approach applies only to loosely defined and standardized factory activities, where it is within the authority of an operative decision maker to forgo the use of the required materials or select to reuse materials. The tactics were not universally accepted as feasible, even in non-value added processes. Only operating materials, of a low value and quantity, were spared by the tactics. Therefore, while this is arguably one of the simplest solutions, it has little application in most firms.

Controlling waste amplifiers encompassed a number of tactics, some of purely technical nature, which requires process specification modifications, while others are controlled with simple scheduling topics and employee trainings, and therefore the average feasibility is comparatively low. The waste amplifier, poor employee qualification can significantly increase waste in almost every manufacturing activity, yielding a broad scope of material waste addressed.

System desensitization to waste amplifiers also investigated some technical measures to improve the robustness of the production system to waste, making some of the tactics unfeasible for certain manufacturers. As this approach also addressed the waste amplifiers, almost every material waste form and activity was addressed.

From this exercise it is clear that the waste mechanisms derived from the model do have practical relevance in the factory, however there is no silver bullet for every manufacturing system. Some of the approaches may conflict with logistical and cost goals, and therefore careful consideration of the repercussions is recommended before acting. The comprehensive method to evaluate the effects of the mentioned tactics on a specific production system is described in the next chapter.

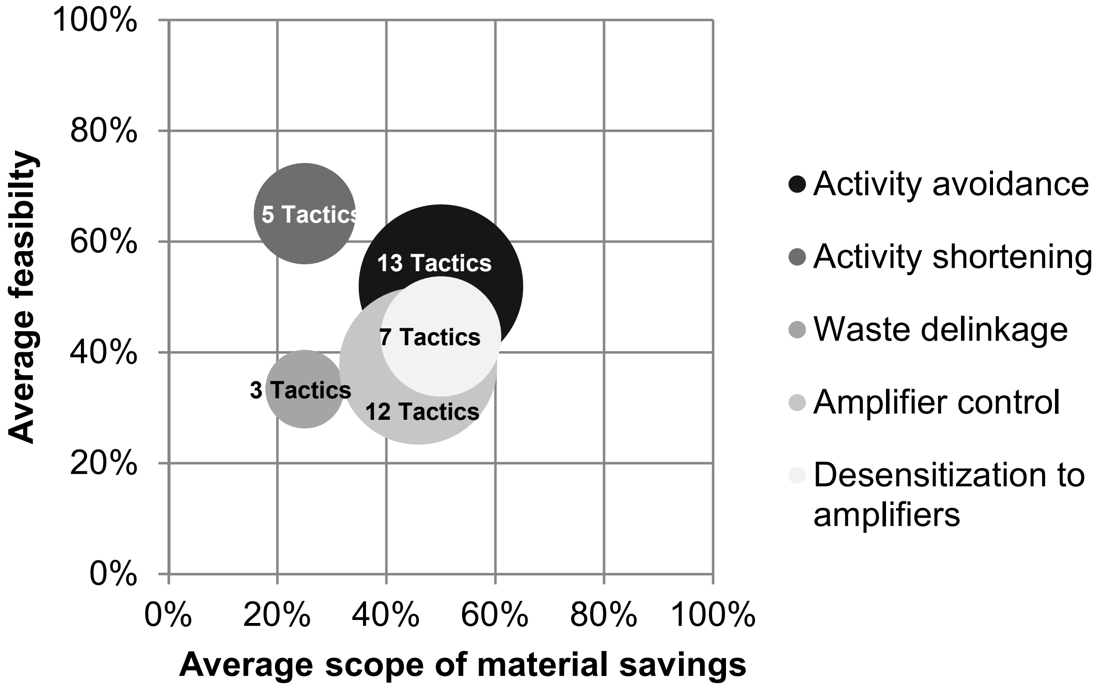



**Figure 41: Potential for material savings through the addressed strategies**

# 7 Method for Improving the Material Efficiency of Existing Production Systems

Based the material efficiency model presented in Section 6, the following section describes a method for modelling and evaluating material efficiency scenarios.

Figure 42 depicts the three blocks of the method. First, a simulation model (Block 1) is utilized to replicate the causal relationships within a factory and predict the amount of accumulated material waste. Secondly, aggregate key performance indicators are calculated and visualized from the simulation results (Block 2), depicting and identifying waste "hot-spots".

The systematic derivation of material efficiency improvement measures and scenario building is detailed in Block 3. The generated scenarios can then be reinvestigated in Block 1, iteratively repeating the cycle.

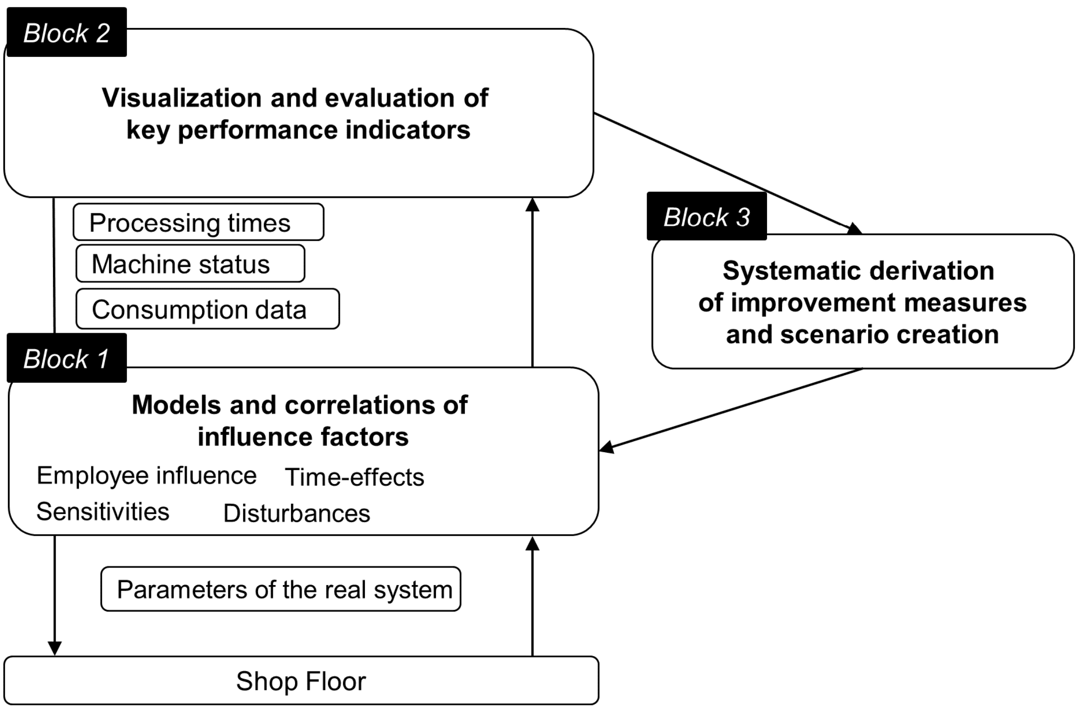



**Figure 42: Method for improving the material efficiency**

## 7.1 Block 1: Simulation Model of a Material-Consuming Manufacturing System

### 7.1.1 Modelling an Operating State-Dependent Material Sink

In continuous simulation, the main module of a material sink evaluates the conditions for maintaining its operating state at every time step. The operating state dictates not only how much material waste occurs, but also the production rate of the system and the corresponding costs of production. For each material sink of the simulation model a separate material sink module is needed.

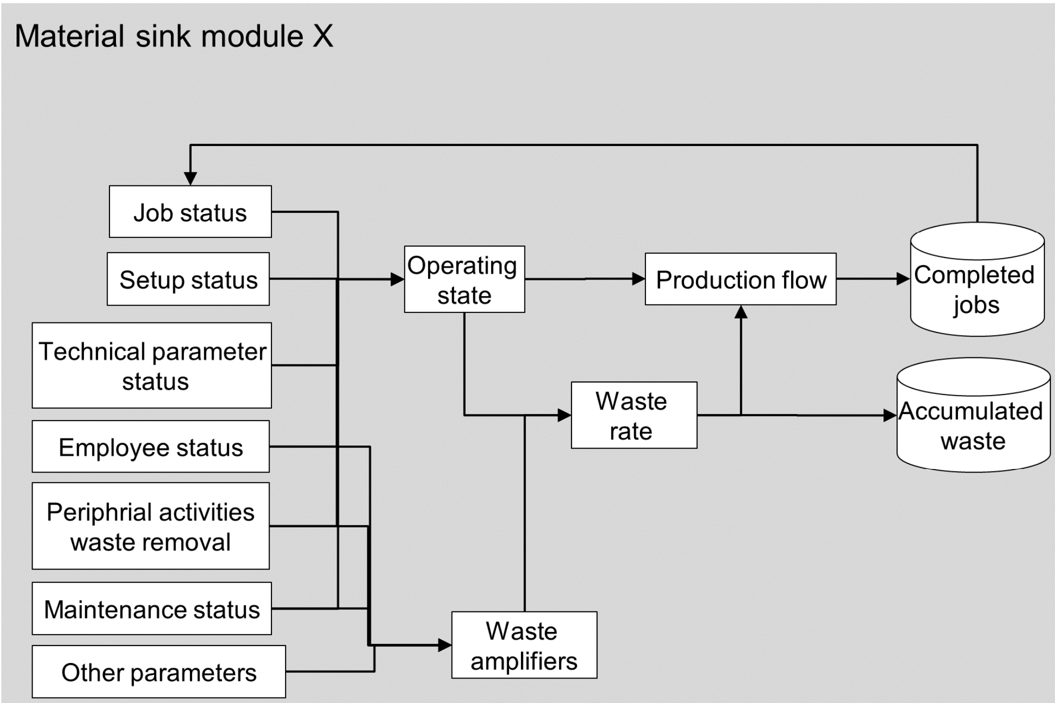



**Figure 43: Components of material sink module in Vensim™**

The operating state logic depends on multiple parameters both within the material sink module, e.g. technical machine parameters and maintenance intervals, as well as stock levels and schedules from upstream or downstream modules.

Boolean logic decides the operating state of the material sink at each time step in the simulation (every minute in the application cases). For the generic operating state logic presented in Figure 38 the implementation is described in detail below and in its Vensim visualization in Figure 71.

The approach used to model the modules of a material sink in a system dynamic software are described below. Readers may refer to the model structures and more comprehensive variable definitions in Appendix A.

**Checking if machine is off:** A PULSETRAIN function is used to distinguish non-working times (e.g. nights or weekends) from working hours. Since most manufacturers adjust their working hours depending on demand, a second condition, checking the stock of processed parts before starting a day of shift of production is added.

**Checking if planned maintenance activities are up-to-date:** A stock and flow set is used to model the time since the last maintenance activity ("MaintTickerS1" and "UptimeS1") (see Figure 72). When the elapsed time exceeds a preset maintenance interval value, the machine enters a "maintenance overdue status". In the generic operating logic, the planned maintenance is executed immediately, represented by the elapsed maintenance activity flow, "ElpMaintS1". After exceeding a constant or condition-dependent duration, the maintenance job is registered as completed. A supporting flow "CompMaintS1" signals the completion and restarts the time-since-maintenance counter flow.

**Checking if technical parameters are in order:** the occurrence of a technical error is modelled as a PULSETRAIN function with a time-to-failure as the pulse frequency and time-to-repair as the pulse duration. Both functions are modelled as normally distributed random functions recalculated following each failure incident, using a stock as a breakdown counter ("BD Count S1"). Parameters of the random functions are extracted from company data (in input spreadsheets). The NOISE SEED is varied from run-to-run to ensure that the model behavior is not contingent on a pseudo-random sequence generated by Vensim™.

**Checking if employee is present and ready:** Short employee absences (e.g. bathroom breaks or for supporting activities) are modelled by a PULSETRAIN function. Employee qualification is modelled as a normally distributed random function recalculated each shift. Parameters of the random function are extracted from a company skills matrix. The employee qualification is compared with a minimum employee qualification for the completion of the next production job (see Figure 82).

**Checking that material feed and removal are in working order:** The machine will idle if there is a technical error either directly upstream or downstream, no material upstream, or the maximum stock for the variant is exceeded (starving and blocking). The material feed and removal are assumed technical systems, with their failure modelled analogously to the technical errors of the main machine. The stock levels, modelled in the stock-management module (see Figure 79), are compared with limits set in this module for each variant.

**Checking if an order is open:** Based on a schedule in the input spreadsheets (see Figure 81) the system loads a series of jobs each day based on their start date. If no jobs are listed in the schedule, the process will go into idle state. If a job is processed, the machine will complete the job when the processed quantity ("Finished S1") exceeds the current job quantity ("Current Job QTY S1") in Figure 74. Alternatively a pull-system can be implemented, where the material sink start to produce a fixed lot size of the product variant with the lowest downstream inventory levels after completing each order. No production schedule is required.

**Checking if the current machine configuration is correct for the next order:** The required machine configuration for each product variant is specified in the input spreadsheets (see Figure 82). For a new job, the required configuration is compared with the existing configuration. If these are not identical, a setup of a combination specific duration is completed based on “Setup Matrix S1” (see Figure 75). To avoid circular logic, a support stock-flow is used to set the current configuration to the desired configuration at the end of the setup.

As soon as the setup time is completed, a work state can be resumed, assuming all other criteria are still fulfilled. In the work state, the specified variant (from the order) is produced at a variant-specific speed. The work state is then ended through the closure of the order after exceeding the order quantity, any incurred quality losses are deducted from the production speed during production. The quality losses deducted are represented by ML M1S1 (material loss through defects) in Figure 74, slightly simplified for transparency.

### 7.1.2 Depicting Peripheral Waste-Causing Activities

Material waste-causing activities that are not driven by the operating state of the main module are depicted in the peripheral module. One of these is the cleaning of the machine and the removal of material waste, which can either take place in fixed intervals (e.g. daily) or on a needs basis (i.e. when the accumulated waste for the material sink reaches a critical value). For example, in one process clean ups are completed once the accumulation of material waste, “Dirt Accu S1” exceeds a fixed “dirt limit” (see Figure 76). For each clean-up, a fixed rate of cleaning product is consumed. The accumulated cleaning waste counts towards the aggregate material waste.

### 7.1.3 Accumulated Waste

The accumulated amount of material waste is modelled as a separate flow-stock-flow chain for each material waste type as shown in Figure 77. System dynamics software cannot distinguish between materials in a single stock, therefore multiple stocks should be used to model different homogenous waste piles. Process defects are modelled as material waste form “1” in all process modules. Unlike other waste forms, the rate of waste accumulated is deducted from the production speed, so that the main module continues to produce until the order quantity of good parts is reached. Aggregate material waste (sums by waste type over all processes) is modelled in the stock management module.

Similarly, from current operating-state dependent material waste rate of each material (“Current Mode MLR S1”) is calculated using the regression model presented in Section 6. The regression coefficients for both cases are located in an Excel™ lookup (see Figure 82). Values of the waste amplifiers are modelled as random normal functions (e.g. employee qualification, “Local Quali S1” in Figure 78) or as material waste dependent (e.g. ambient conditions, “AC Unsuitability S1”).

Material waste flows attributed to transitions are dependent on the current material waste quantity (“Current Trans MLA S1”). The value of the material waste quantity is only held for one-time step (i.e. transition duration = 1 min). In all cases the material waste accumulates over time, until it is disposed of by a peripheral housekeeping activity (see 7.1.2).

### 7.1.4 Modelling Logistical Performance

While the last few sections have focused on modelling the amount and cost of material waste, this thesis strives to identify material efficiency solutions without sacrificing logistical performance. The logistical performance of the system is modelled in the KPI monitoring module (see Figure 80) and briefly described below.

Total material cost is calculated as the sum of the material cost of good parts and the material waste cost (raw material purchase price and the disposal costs). The machine depreciation is modelled linearly over the simulated period, assuming a write-off period of 20 years. The labor cost is a qualification dependent hourly rate a machine sink that is not in an "off" state, this may be a fraction of an hourly wage in the case of multiple machine operation. The machine utilization for each material sink can be modelled as the ratio of the hours spent in a "work" state to the total number of hours in the simulated period. The cost per piece can be calculated as the sum of all cost stocks divided by the throughput for all product variants.

The average throughput time of the system is estimated by dividing total inventory level of the system by the average daily customer demand, resulting in "days of inventory". The delivery reliability can be measured by comparing an ideal dispatch flow (based on job due dates) with the actual shipment dates.

## 7.2 Block 2: Visualization of Key Performance Indicators

To facilitate the identification of material-cost-intensive activities and operating states, an Excel™ evaluation tool breaks down the material cost by process and activity, as shown in Figure 44. The input of data is either manual for initial measurements or semi-automated for simulated scenarios.

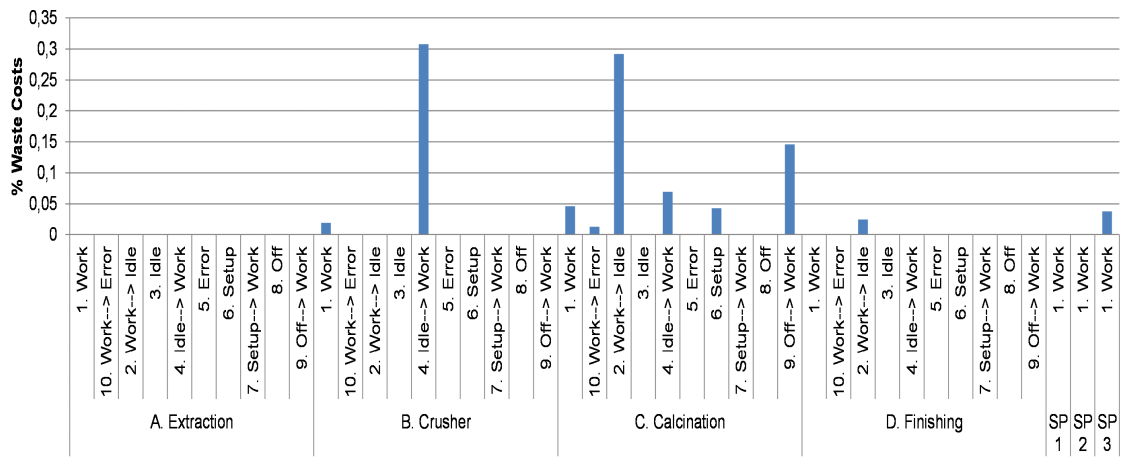



**Figure 44: Material losses by operating state in lime plant**

At the process level, material intensity webs depict the behavior of the machine module more intuitively. The web depicts the operating states as bubble, with the bubble size representing the portion of time spent in the operating state, and the deepness of the color representing the material lost material value in this operating state per unit of time (see Figure 45). The material loss through state-transitions is represented by connecting arrows between the operating state bubbles. The thickness represents the quantities of the transition in the simulation period, while the deepness of the color represents the material intensity of the state transition.

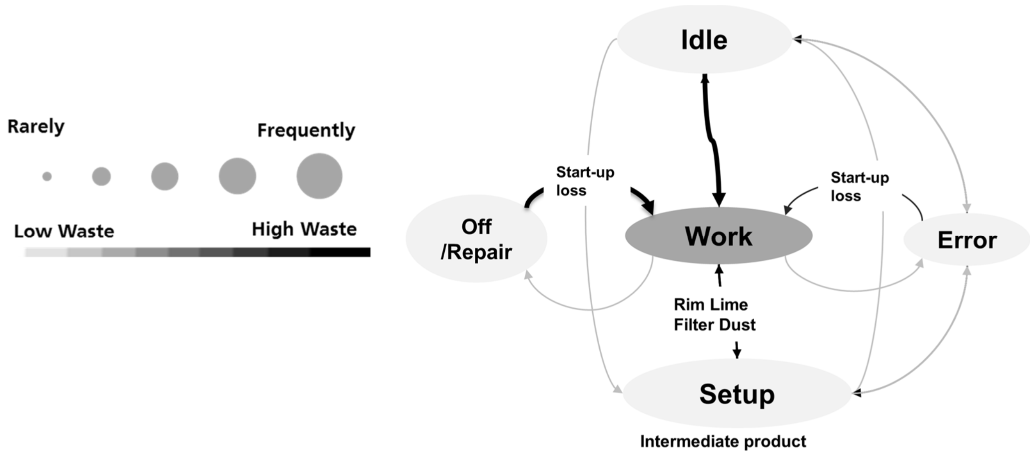



**Figure 45: Material intensity web for a calcination process**

## 7.3 Block 3: Generation of Improvement Measures and Scenario Creation

To define improvement scenarios to investigate in a simulation, a three-step approach is recommended. After visualizing the most costly material waste forms (see Section 7.2), the user enters these into a semi-automated improvement measure generator. In a two-step process, the generator characterizes the material waste forms, and selects only relevant improvement measures from the library for this type. In a third step, scenarios are planned for simulation. These three phases are pictured in Figure 46.


**Figure 46: Improvement measure generation process**

### 7.3.1 Characterizing Material Waste Forms

Starting from a material waste break down and material waste web (see Figure 44 and Figure 45) the most mass- and cost-intensive material waste forms are identified.

Based on their triggering activity, an Excel™-based improvement measure generator (see Figure 83) categorizes the waste forms by the criteria shown in the morphological box in Table 21.

**Table 21: Material waste characterization by activity type**

| | Manifestations | |
|---|---|---|
| Nature of activity occurrence | Planned | Unplanned |
| Desirability of activity occurrence | Value-adding | Non-value-adding |
| Material waste quantity per activity | Duration-dependent | Duration-independent |

Only work-piece and machine-batch processing are considered value-adding. The other activity classifications are shown in Table 9.

### 7.3.2 Selection of Improvement Measures

Once the character of the material waste is known, the improvement measure generator selects the most appropriate improvement measures from a library, under the premise that not all material waste control strategies (see Section 6.6) are applicable for all material waste types, as shown in Figure 47. For value adding activities, with rigid processing speeds and minimum volume quantities, the material waste can only be controlled over the occurrence and duration mechanisms by avoiding unnecessary processing, e.g. processing defective parts or unneeded parts. For duration-independent waste from value adding activities (e.g. startup losses) changing lot sizes to increase run length may be effective. For some operating materials, a delinkage strategy may be possible. Adjusting the material waste rate and amounts via waste amplifier control is universally applicable.

| Material waste type | Applicable control strategies: Activity occurrence | Activity duration | Delinkage | Amplifier control | Amplifier desensitization |
|---|---|---|---|---|---|
| Duration-dependent/ Value-adding activity | ◐ | ◐ | ◐ | ● | ● |
| Duration-independent/ Value-adding activity | ◐ | ○ | ○ | ● | ● |
| Duration-dependent/ Non-value-adding activity | ● | ● | ◐ | ● | ● |
| Duration-independent/ Non-value-adding activity | ● | ○ | ◐ | ● | ● |
| Duration-dependent/ Unplanned event | ● | ● | ◐ | ● | ● |
| Duration-independent/ Unplanned event | ● | ○ | ◐ | ● | ● |

***Scale:***

●: control strategy is possible and effective in most cases

◐: control strategy is ineffective in some cases or may present trade-offs

○: control strategy is ineffective in most cases

**Figure 47: Recommended control mechanisms for each material waste type**

As mention in 6.6, controlling activity duration is only applicable for waste flows that occur at a time-dependent rate, not those that occur in fixed quantities. The delinkage mechanism is only applicable in very few cases, where the material consumption is not subject to process or product specifications.

A full list of the improvement measure library as well as the user-interface of the improvement measure generator is provided in Table 31.

### 7.3.3 Scenario Development

With the improvement measures and corresponding parameter adjustment suggestion from the improvement measure generator, the user can now develop scenarios by combining multiple improvement measures (at the same time or with delay in the simulation.

The parameter changes are generally executed over the input spreadsheets (see Figure 82) though changes to the operating state logic require direct changes in the Vensim™ model.

## 7.4 Procedure for Practical Application

The following procedure offers a structured approach for practitioners applying the method. An overview of the procedure is shown in Figure 48.

**Step 1: Setting system limits**: Logistically and organizationally decoupled or physically distanced process chains generally yield fewer interdependencies that warrant dynamic simulation. Accordingly, the boundaries should be set to a group of processes with a logistical connection or those in direct proximity of one another.

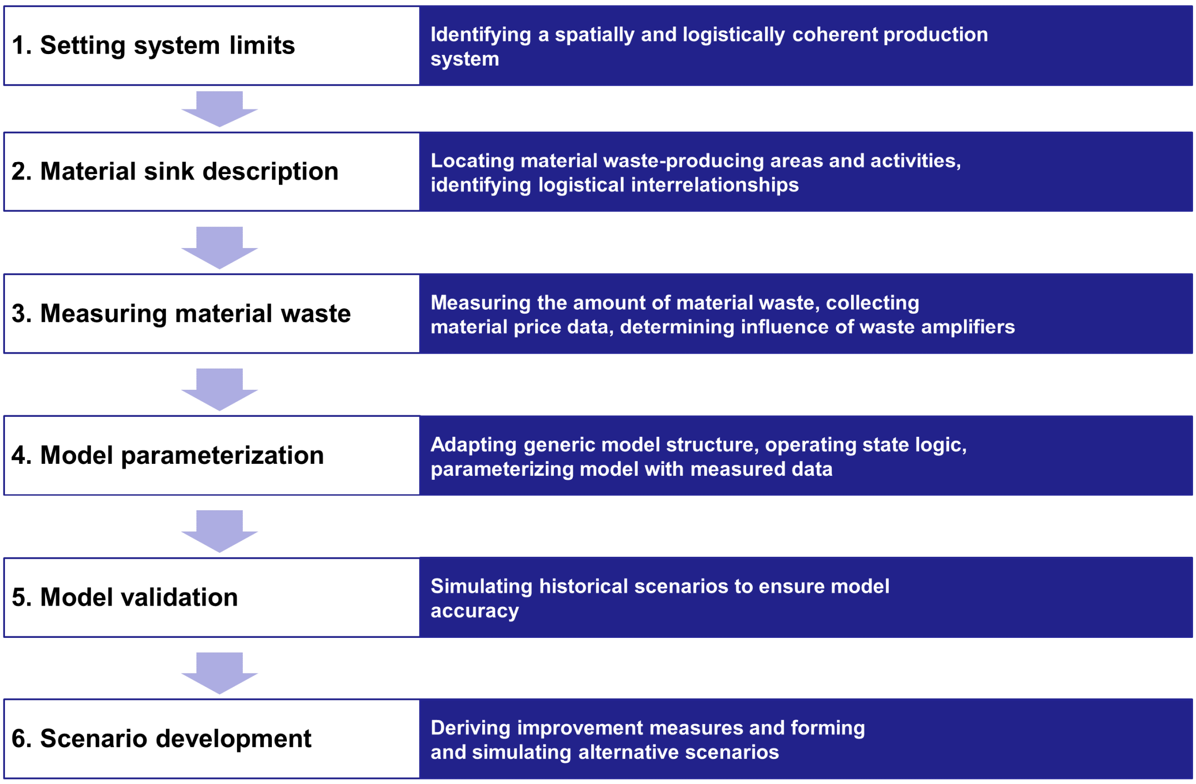



**Figure 48: Practical application procedure**

**Step 2: Material sink description:** A prerequisite to this method is the correct allotment of material waste to its point of occurrence (material sinks).

Therefore, root-cause-analysis is recommended before modelling the occurrence of process defects.

Every machine-module and stockpile within the system limits, where material waste occurs should be modelled as a material sink. Additionally, processes that are waste-free, but are linked with other, waste-producing processes must be modelled as a material sink without material consumption.

Conducting interviews with process experts to adapt the generic operating state logic to the real operating state behavior of each material sink is recommended (see Figure 38).

**Step 3: Measuring material value loss rates:** Material waste measurement in short time-intervals is necessary to catch different operating states and operating state transitions and calculate the material waste rates and material waste quantities for each activity. Technology can support the task of waste tracking, for instance if automated process inspection technology is installed directly after the process to accurately recording process defects to the correct operating state period. Similarly, sensor technology coupled with scales or cameras can estimate flows of material exiting the workstation or entering a scrap container. For fluid materials, ultra-sonic measurement equipment may be used to estimate waste flow rates. For infrequent activities, the material lost may be estimated from procurement data.

The Pareto principle proves useful for selecting big-hitter material waste forms for regression analysis with waste amplifier factors. In the application cases, less than three material waste forms per case made up 80% of the material waste costs. By cross-referencing shift protocols with skills matrixes and ambient condition data, no additional data collection may be needed in some cases.

**Step 4: Model parameterization:** When the data collection is complete, a process module should be created for each process material sink, while material losses via inventory deterioration are modelled in the inventory overview module. If the operating mode logic has changed, the if-statements under the parameter "op-state" of each material sink should be adapted. Otherwise, the model parameterization with process variant data, production sequences and lot sizes, as well as process data (e.g. MTTF) should be entered in the input spreadsheets without changing the model structure.

**Step 5: Model validation:** To ensure the model is accurately depicting real-world behavior, a simulation of a selected historical reference period should be simulated at this point. It is important that no exceptions to the operating mode logic were made in the historical period. If the key performance indicators in the evaluation model vary more than 10% from the real values, the model is not correctly parameterized and step four should be repeated.

**Step 6: Deriving improvement measures**: Using the visualization tool, the material intensive processes and operating states are visible. The tool can be used either using simulation results depicting a recent period or by entering the measured data directly into the tool.

# 8 Application in an Industrial Environment

In the following section, the application of the developed method is shown for three manufacturing systems utilizing the practical procedure described in Section 7.4.

## 8.1 Aluminum Parts in the Automotive Sector

An automotive supplier manufacturers small aluminum parts for gasoline engines in a five-stage production process. Raw aluminum slugs are lubricated, impact extruded, cut to remove excess material, hardened in a three-step heat-treatment process, and finally shot peened with stainless steel shot. In the impact extrusion work center five presses and three cutting machines process all product variants interchangeably. The production facility produces roughly 30 part variations, differing in geometry (dies), and in slug mass.

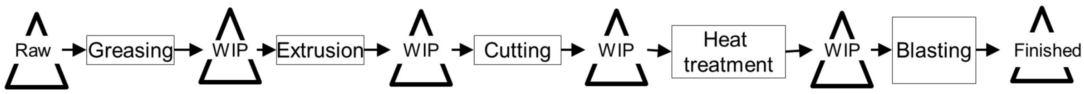



**Figure 49: Process chain of aluminum parts**

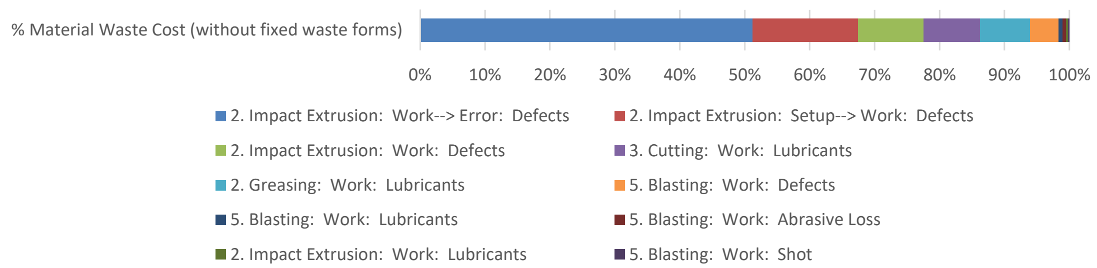
**Step 1: Setting the system limits:** Company management selected a product family manufactured in a dedicated area, spatially isolated from other product lines, for the simulation study (shown in Figure 49).

**Step 2: Material sink description:** the material sinks in the process chain are shown in the rectangles in Figure 49. Negligible amounts of transport losses and inventory shrinkage are reported in the last two quartiles, therefore the stockpiles are not considered material sinks. Workshops with process experts yield an adapted operating state logic without machine idling due to employee absence, since the machines only require supervision to perform intermittent quality checks and readjust tool settings. The employees each operate 1-2 presses and a cutting machine in multiple machine operation, with a team lead to support quality checks and setups if needed.

**Step 3: Measuring material waste at the material sinks:** through process observation and staff interviews the material waste forms of the considered material sinks are determined and assigned to the machine module or its peripheral areas. Measurements of material waste are recorded on the shop floor and supplemented with employee protocols. Assignment of the material waste to operating state, operating transition, activity or event provides a breakdown of the material waste costs, as shown in Table 22.

**Table 22: Material waste forms for aluminum part production**

| Material sink | Waste form | Activity | % Material waste cost |
|---|---|---|---|
| 1. Greasing | Grease | Work | 1% |
| 2. Greasing | Lubricants | Work | 4% |
| 2. Impact extrusion | Defects | Work--> Error | 25% |
| 2. Impact extrusion | Defects | Setup--> Work | 8% |
| 2. Impact extrusion | Defects | Work | 5% |
| 2. Impact extrusion | Lubricants | Work | 0% |
| 3. Cutting | Chips (fixed) | Work | 53% |
| 3. Cutting | Lubricants | Work | 4% |
| 5. Blasting | Lubricants | Work | 0% |
| 5. Blasting | Shot | Work | 0% |
| 5. Blasting | Abrasive loss | Work | 0% |
| 5. Blasting | Defects | Work | 2% |




Three "biggest hitter" waste forms, highlighted in light blue in Table 22, amounting to 80% of the total non-fixed material waste cost, are selected for a detailed regression analysis of the waste amplifiers and the waste quantity per incident or waste rate per time unit. However due to company policy, some of the waste forms are consistently the same quantity, e.g. 1 small bin of parts

(~ 50 parts) is discarded after startups, because a 100% visual quality test is not economical (setup→ work defects). For the same reason, a large bin of parts (~500 parts) is discarded after tool inserts break (work→ error defects). A regression analysis is only completed for extrusion defects in work state for this reason.

**Regression analysis:** The waste rate (defects per minute) is calculated for ~700 production orders based on shift protocols in a 3-month period. Methods for measuring the waste amplifiers (predicting variables), are described below and summarized in Table 23.

- Part discommonality factors rooted in part geometry is determined in a process-expert workshop, here two levels of subfamilies can be distinguished: The discommonality is set to 0 if the previous part ordered on the machine is identical, 1 if in the same subfamily, and 2 otherwise. This is completed for all ~700 observations.
- Poor-machine-and product variant-fit is calculated by first determining the average defect rate for each combination and an average defect rate for each product variant overall, as described in Table 23.
- Poor machine condition is modelled as the elapsed time since the last planned maintenance activity at the order start time for simplicity.
- The production run length is based on the order start-and end times in the shift protocols.
- Employee qualification data is taken from a skills matrix. Skills scores from both work center-specific qualification and general qualifications are summed. These represent both the technical qualification and the employee's cost and environmental consciousness.
- Temperature and air humidity are frequently blamed for high defect rates. To investigate these effects, weather data from a local weather station is used, since the observations are made in summer months in a non-climate-controlled factory hall.

**Table 23: Waste amplifier measurement**

| Waste amplifier | Measurement method |
|---|---|
| Discommonality of successive product variants | $\{x, y\} \in A \rightarrow$ Discommonality = 0<br>$\{x, y\} \notin A \wedge \{x, y\} \in B \rightarrow$ Discommonality = 1<br>$\{x, y\} \notin A \wedge \{x, y\} \notin B \rightarrow$ Discommonality = 2<br>where<br>x : current variant<br>y: previous variant on the same machine<br>A: same part (same / very similar parts)<br>B: same sub family (similar parts) |
| Poor fit of machine assignment and product variant | Poor fit degree = $WR_{Machine}$ / $WR_{All}$<br>where<br>$WR_{Machine}$: average waste rate for machine – product variant combination<br>$WR_{All}$: average waste rate for product variant on all machines |
| Poor machine condition | Elapsed time since maintenance = end time of last PM activity – order start time |
| Long run length | Run length = Order end time – Order start time (hours) |
| Low employee qualification and cost-consciousness | Skill score of responsible operator (Company skill matrix) |
| Unfavorable ambient conditions | Daily high temperature<br>Daily mean temperature<br>Daily average air humidity |
| Holding time | Start time production – time of raw material receipt<br>Start time production – time of greasing |

In a multiple linear regression analysis, three of the waste amplifiers demonstrated a statistically significant correlation (P-value<0.05) with the average waste rate (kg/minute) for extrusion defects in work-state. These waste amplifiers are employee qualification (inversely proportional), run length (inversely proportional), and poor machine condition, represented by time since maintenance (proportional), as shown in Figure 50. Nonlinear correlations are also investigated (e.g. employee qualification squared), but yielded higher p-values than their linear counterparts in this case. However, it is recommended to investigate both linear and nonlinear regression models in practical application.

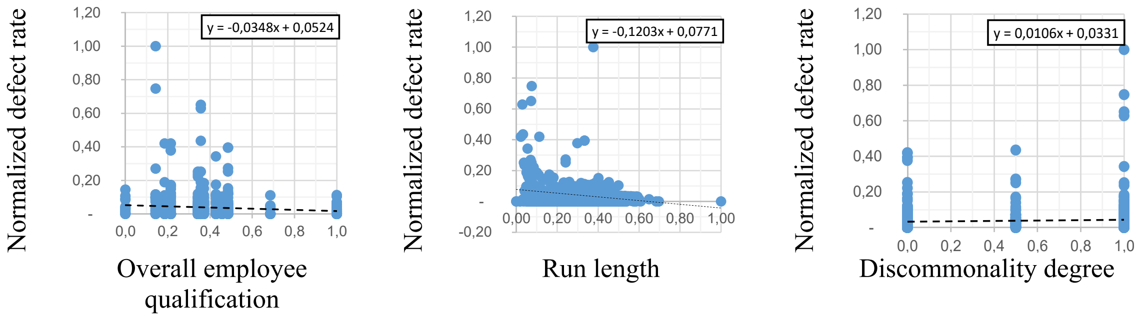



**Figure 50: Extrusion defect waste rates a function of waste amplifiers**

**Step 4: Parameterization of a simulation model**: Expert interviews, shift protocols, power measurements, and ERP system data provide the master data for the production model. Along with cost data from controlling, the case specific data is integrated into the input spreadsheets (see Figure 81) linked with the Vensim™ model, so that the same base simulation model can simulate multiple case studies with few parameter adjustments in Vensim™.

**Step 5: Verification of base line:** To ensure the model accurately represents reality, the production of four two-month time periods are reproduced in the model. A sensitivity analysis is used to investigate the influence of model parameters on the model throughput and material cost efficiency.

| KPI | Simulation results (% Static calculation) |
|---|---|
| Volume | 110,7 % |
| Throughput time | 91,3% |
| Waste | 108,4% |

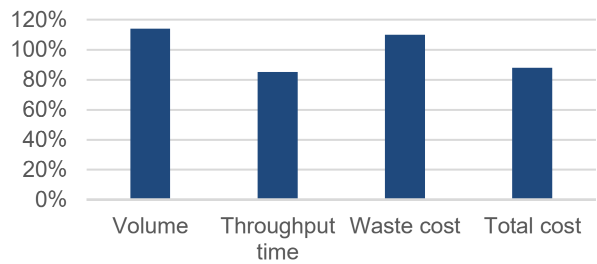



**Figure 51: Verification of aluminum parts simulation model**

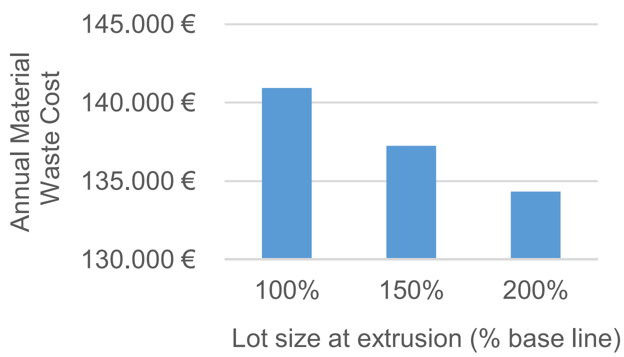
Step 6: Derivation of improvement measures and scenario creation:

Using the visualization tool and the improvement measure generator (see Figure 83) four waste reduction scenarios are identified in Table 24.

**Table 24: Simulated scenarios for aluminum parts manufacturer**

| Improvement scenario | Addressed waste form | Parameter adjustment |
|---|---|---|
| 1. Larger extrusion lots for less startup loss | Startup losses (setup→ work), defects in work mode | + Production order sizes |
| 2. Shorter reaction time to tool failure at extrusion (e.g. increased employee presence) | Defects (work→ error) | - Lessen waste quantity |
| 3. Higher employee qualification | Defects in work mode | + Min employee qualification<br>+ Mean employee qualification |
| 4. Sequence products by similarity (campaigns) | Defects in work mode | + Change part sequences or next variant logic |

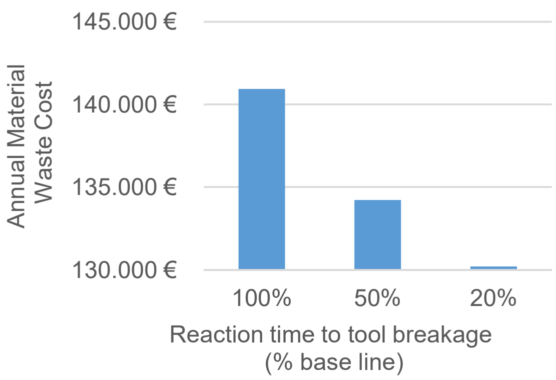
For Scenario 1, the production order sizes are varied from their current value to investigate their effect on waste generation and overall performance in the dynamic system, as shown in Figure 52. Due to the comparatively small material loss quantity through at setups, the scenario exhibits small savings in material waste cost, while inventory levels increase dramatically and the service level suffers.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Lot size | Material cost efficiency | Average serviceability | Average throughput time | Other costs |
| 100% | 100,0% | 100,0% | 100,0% | 100,0% |
| 150% | 102,7% | 91,0% | 117,0% | 98,0% |
| 200% | 104,9% | 88,5% | 144,5% | 99,1% |

**Figure 52: Results of lot size variation (Scenario 1)**

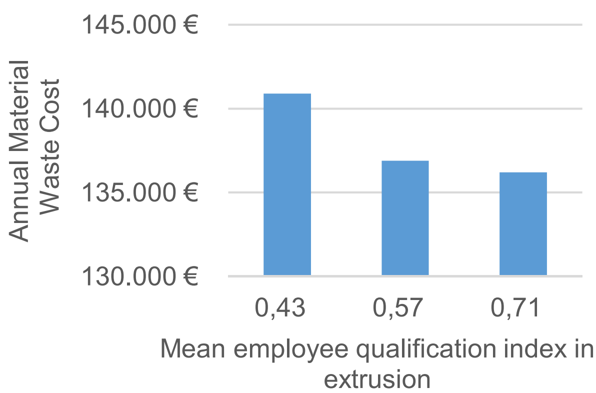
In Scenario 2, shorter reaction times lessen the waste quantity from 500 pcs to 250 pcs or 100 pcs per incident. This reduction yields material savings of 10.000€ annually (see Figure 53). It is assumed that with better timing, the current staff could catch these breakages within 2 minutes; however, the cost savings would not justify another employee in the area or an automated solution.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Reaction time | Material cost efficiency | Average service-ability | Average throughput time | Other costs |
| 100% | 100,0% | 100,0% | 100,0% | 100,0% |
| 50% | 101,8% | 99,5% | 99,5% | 98,2% |
| 20% | 104,8% | 99,7% | 98,7% | 99,0% |

**Figure 53: Shortening reaction time after tool breakage (Scenario 2)**

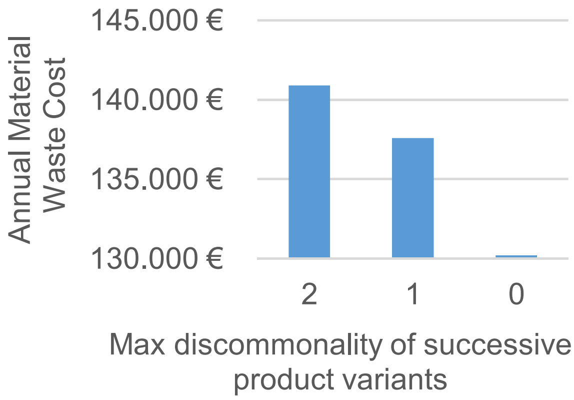
Scenario 3 investigates the effect of increasing employee qualification in impact extrusion on material waste costs and performance. A moderate increase in qualification leads to a total material cost savings of roughly ~5.000€ annually as shown Figure 54. Assuming high employee retention, a qualification package for training for the extrusion operators would pay for itself in 1-2 years.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Mean skills index | Material cost efficiency | Average service-ability | Average through-put time | Other costs |
| 0,43 | 100,0% | 100,0% | 100,0% | 100,0% |
| 0,57 | 101,3% | 99,7% | 97,1% | 98,7% |
| 0,71 | 101,3% | 99,8% | 98,0% | 99,4% |

**Figure 54: Results of employee qualification variation (Scenario 3)**

Scenario 4 examines the effect of higher commonality of successive parts on each machine on the extrusion defect rate. Due to the larger regression coefficient, larger material savings are seen in Scenario 4 than Scenario 3, though Scenario 3 presents fewer trade-offs with market performance.




| Results (% base line)) | | | | |
|---|---|---|---|---|
| Max dis-commonality | Material cost efficiency | Average service-ability | Average through-put time | Other costs |
| 2 | 100,0% | 100,0% | 100,0% | 100,0% |
| 1 | 102,7% | 93,6% | 116,1% | 98,0% |
| 0 | 105,3% | 88,6% | 129,5% | 99,1% |

**Figure 55: Product variant sequencing for less discommonality (Scenario 4)**

Overall, the first case study focused on the extrusion press process due to the quantity and cost of the waste generated in the work center, particularly due to the short service times of the tooling inserts. This indicates that limiting defect rates, especially during instable periods, is the largest control lever for material efficiency for some manufacturers.

After implementing an employee-training program to increase the overall qualification of employees in the impact extrusion area, the material cost savings attained were roughly 30% greater than the simulation results.

## 8.2 Small Batch Brandy Distillery

In a brandy distillery, spirits are distilled from fruit varieties or wine yeast in batches. Small distilleries frequently manufacture both high-quality fruit brandies for bottling and direct sale, as well as lower quality neutral alcohol for delivery to larger distilleries, and perform contract distilling to fully utilize the distilling equipment and salvage to byproducts of agriculture (e.g. wine yeast).

**Step 1: Setting the system limits:** The system consists of multiple fermentation tanks, a single distilling vessel, a single filtration machine, and bottling line. Therefore, all brandy varieties using the vessel are considered. A period of a year is set for consideration, due to the few working days annually.

**Step 2: Material sink description:** For fruit brandies, raw fruit is mashed, fermented, and distilled in a small batch process, where the output is then separated into pre-run, mid-run, and post-run material by alcohol content. Pre-run and post-run are added to the subsequent batches, until the permitted working time is over, at which point the pre-run and post-run are discarded. The mid-run is then aged, cooled, diluted, filtered, and bottled. For wine yeast, mash is already fermented at the time of purchase. An overview of the process shown is shown in Figure 56.

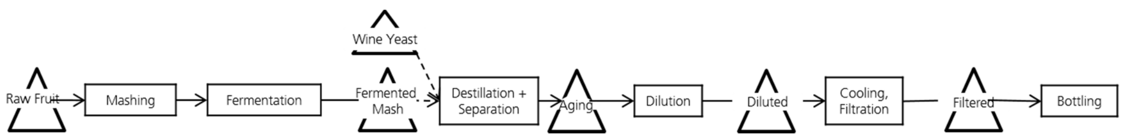



**Figure 56: Distillery process chain**

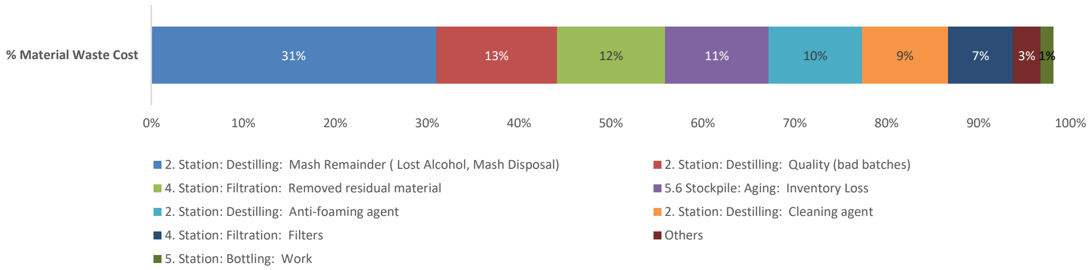
**Step 3: Measuring material waste at the material sinks:** Over a period of a year, material value loss incurred through these waste flows is measured and tracked (see Table 25). Since brandy is a natural product, the yield, i.e. the effectiveness of the transformation into pure alcohol, varies. Undesirable aromas in the brandy can warrant discarding the whole batch. While management assumes batch sequence in the distilling process is responsible for undesired aromas, no formal batch sequencing method is utilized. An anti-foaming agent is dispensed manually into the vessel with each batch to limit foam production during distilling, and is ejected with the process water at the end of the process. Cleaning materials are used to remove residues from the vessel before running top quality products, a labor-intensive process. Pre-run and post-run of the last batch are discarded at the end of the day, representing a rigid byproduct. Undesired aroma changes account for inventory deterioration, most significantly in the finished goods stock. The distillation vessel is heated with oil that is considered in the production costs, but not as a material (see Section 2.3)

The filtration process uses multiple-use filters, with a fixed life span. Before filtering another product, the pump and the hoses of the filtration machine are flushed and the remainder of the previous product is lost.

Due to the infrequent manual bottling process, a few labels and glue applications are discarded at the beginning of a bottling lot. Bottles and caps are occasionally damaged or broken.

**Table 25: Material waste forms for brandy production**

| Material sink | Waste form | Activity | % Material waste cost |
|---|---|---|---|
| 2. Station: Distilling | Mash remainder (incl. lost alcohol) | Work | 31% |
| 2. Station: Distilling | Defects (bad batches) | Work | 13% |
| 2. Station: Distilling | Anti-foaming agent | Work | 10% |
| 2. Station: Distilling | Cleaning agent | Work --> Setup | 9% |
| 2. Station: Distilling | Byproduct: pre-run, post-run | Work | 3% |
| 2.3 Stockpile: Aging | Inventory loss | Deterioration | 0% |
| 4. Station: Filtration | Removed residual material | Work--> Setup | 12% |
| 4. Station: Filtration | Filters | Work--> Error | 7% |
| 5. Station: Bottling | Wasted labels and glue | Work | 1% |
| 5. Station: Bottling | Wasted labels and glue | Setup--> Work | 1% |
| 5. Station: Bottling | Dropped bottles | Work | 1% |
| 5. Station: Bottling | Wasted bottle caps | Work | 0% |
| 5.6 Stockpile: Aging | Inventory loss | Deterioration | 11% |




**Regression analysis:** Using the Pareto principle, a regression analysis investigates the effects of the waste amplifiers on the material waste rates and material waste quantities of a few material waste forms accounting for 80% of the material waste costs. Because a single employee is responsible for most of the production orders, a correlation with employee qualification is not considered. Similarly, machine-product variant fit is not considered for this system with single production resources for the processes of distilling, filtration, and bottling.

A scale for brandy variant discommonality, defined by process experts, represents the unidirectional intolerance of lighter aroma products to dominant aroma products in Table 26, while the other waste amplifiers are measured similarly to case study 1 (compare Table 26).

**Table 26: Waste amplifier measurement for distillery**

| Waste amplifier | Measurement method |
|---|---|
| Discommonality of successive product variants | Flushing between variants→ Discommonality = 0<br>{x, y} ∈ A→ Discommonality = 0<br>Ar(x)<Ar(y) ∧ {x, y} ∈ B → Discommonality = 1<br>Ar(x)>Ar(y) ∧ {x, y} ∈ B → Discommonality = 2<br>Ar(x)<Ar(y) ∧ {x, y} ∉ B → Discommonality = 3<br>Ar(x)>Ar(y) ∧ {x, y} ∉ B → Discommonality = 4<br>x : current variant<br>y: previous variant on the same machine<br>Ar: aroma intensity of product variant<br>A: fruit variety<br>B: fruit family (e.g. apple-pear-quince family, cherry family) |
| Poor machine condition | Elapsed time since maintenance = end time of last PM activity – order start time |
| Long run length | Run length = production end time – production start time (hours) |
| Unfavorable ambient conditions | Daily high temperature<br>Daily mean temperature<br>Daily average air humidity |
| Holding time | Production start time (distilling) - Production end time (mash preparation)*<br>Time of tasting – production end time distilling**<br>*Distilling waste forms<br>**Inventory deterioration |

Twelve months of production data (lost alcohol in the mash) revealed a significant correlation between lost alcohol in the mash and the hours that the distillation vessel had already been working, as shown in Figure 57, left. Neither ambient conditions at the time of distilling or mash preparation nor the holding time yielded a significant correlation with yield.

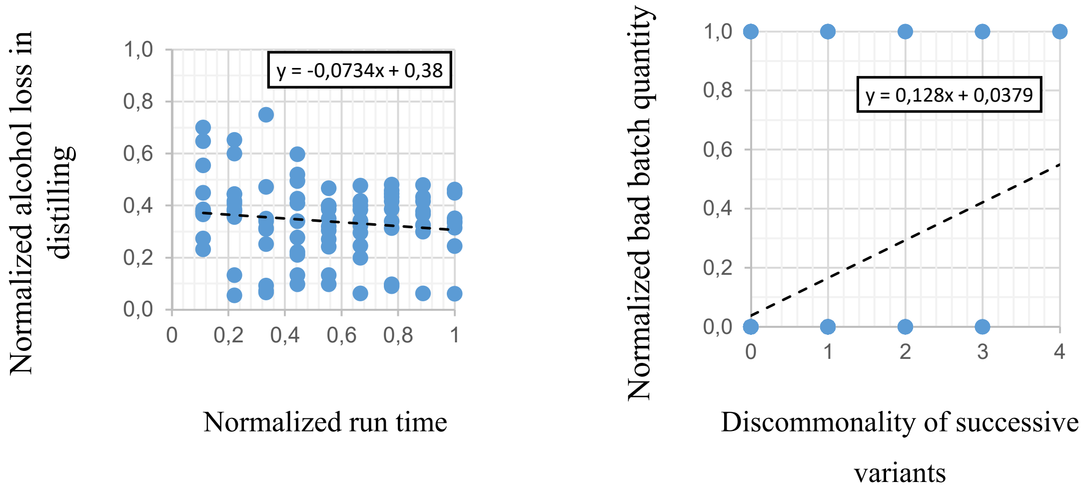



**Figure 57: Waste amplifiers in distilling**

A regression analysis for all batches presented a correlation between discommonality of successive product variants in distilling and the occurrence of bad batches (see Figure 57 right).

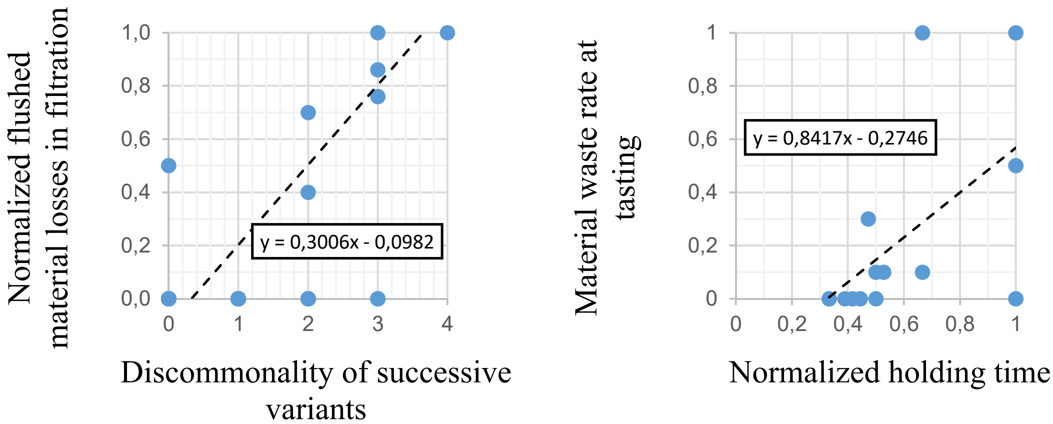



**Figure 58: Waste amplifiers downstream from distilling**

Multiple reasons warrant flushing and disregarding the contents of the filtration machine, including product variant discommonality (see Figure 58 left). Inventory deterioration is only identified when a bottle of a batch is opened before a customer tasting and significant unpleasant changes in taste warrant discontinuing sales. For the reported cases, no significant difference in holding conditions (ambient conditions) is observed and therefore only a regression model with holding time is presented (see Figure 58 right).

While the manually dispensed quantity of an anti-foaming agent varies by batch, no correlation is identified with the waste amplifiers.

**Step 4: Parameterization of a simulation model**: as addressed and shown in 6.4, the material waste accumulation through duration-independent events and activities (e.g. discarding whole batches) can be modelled either with a regression model based on the waste amplifiers (as shown) or with a certain probability during the activity based on parameters (waste amplifiers). To standardize the model, the regression model is used.

Step 5: Verification of base line:

Following the parameterization the reference period (1 calendar year) is simulated. To ensure the model reflected the cost and market performance of the real system, the average of 200 simulation runs is compared with static calculations based on measurement (see Figure 59).

| KPI | Simulation results* (% Static Calculation) |
|---|---|
| Volume | 95% |
| Throughput time | 90% |
| Waste cost | 86% |
| Other costs | 90% |

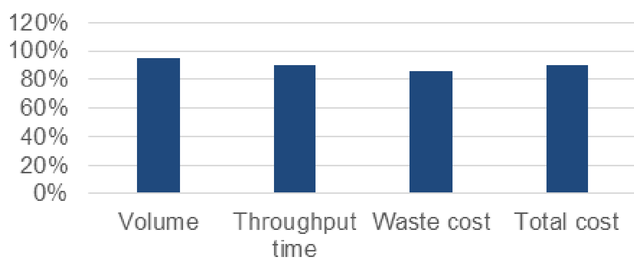



**Figure 59: Verification of distillery simulation model**

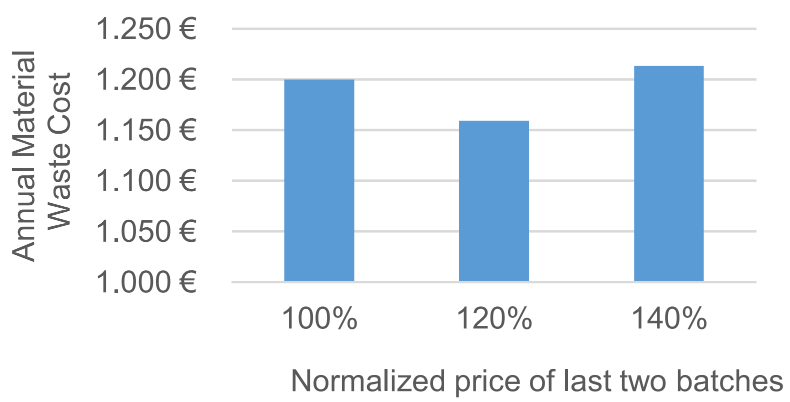
Step 6: Derivation of improvement measures and scenario creation:

Due to the regulation of distilleries, some of the improvement measures are not possible, including prolonging the daily working hours to increase alcohol yield. While the amount of alcohol lost may not be controllable, the material costs can be steered by processing higher cost mash in the later hours of the day. This strategy is examined in Table 27, along with strategies to reduce bad batches, discarded remainder material, and inventory deterioration.

**Table 27: Simulated scenarios for distillery**

| Improvement scenario | Addressed waste form | Parameter adjustment |
|---|---|---|
| 1. Higher cost product variants later in the day | Distilling: Lost alcohol in mash in work mode | Product variant sequence (low price-to-high price) |
| 2. Product sequencing: light to dominant aroma | Distilling: Bad batches in work mode | Product variant sequence (light aroma to stronger aroma) |
| 3. Higher employee qualification | Filtration: residual material purging | Product variant sequence (light aroma to stronger aroma) |
| 4. Shorter holding times | Inventory deterioration (aromas) | Pull-production |

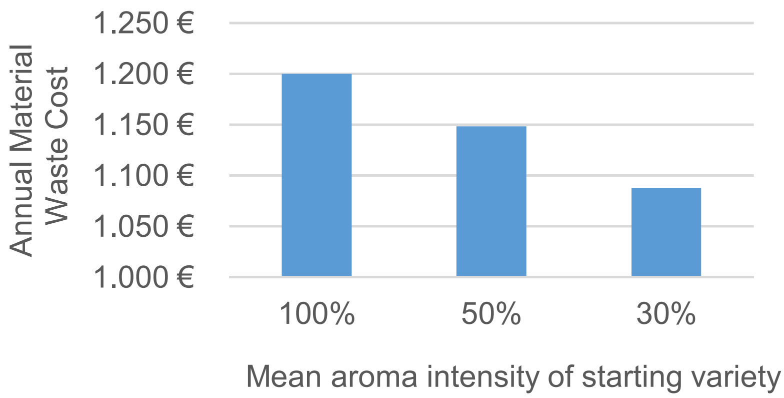
The production schedule logic is adjusted to give premium brandies priority later in the day for Scenario 1. However due to the lightness of the aroma of some premium products, this strategy increases the likelihood of expensive bad batches, negating benefits in material cost, as shown in Figure 60.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Price of varieties in the last two batches | Material cost efficiency | Average serviceability | Average throughput time | Other costs |
| 100% | 100,0% | 100,0% | 100,0% | 100,0% |
| 120% | 103,5% | 97,0% | 101,6% | 110,5% |
| 140% | 98,9% | 98,5% | 98,0% | 101,3% |

**Figure 60: Results price-based product sequencing (Scenario 1)**

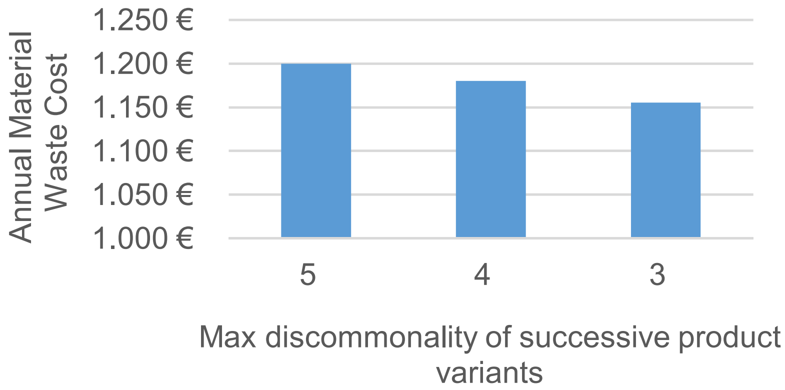
Following the alternative strategy, light aroma products, including premium products are run first in Scenario 2 (see Figure 61). This however leads to lower, more expensive yield, though fewer expensive bad batches occur.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Aroma intensity of starting variety | Material cost efficiency | Average serviceability | Average throughput time | Other costs |
| 100% | 100,0% | 100,0% | 100,0% | 100,0% |
| 50% | 104,5% | 98,6% | 101,2% | 97,7% |
| 30% | 105,6% | 98,5% | 98,0% | 101,1% |

**Figure 61: Results of aroma-based product sequencing in distillery (Scenario 2)**

An aroma-based product sequence is also investigated at the filtration station. Since the filtration equipment is usually used to fill up only a few batches to fill a customer order, restrictive product sequencing had a negative effect on serviceability. It also required more employee time to schedule the batches, lengthening the filtration process (see other costs in Figure 62). Therefore, this approach is not recommended. If the volumes increased, a second filtration device or a recovery system may present a solution to reduce flushing frequency.

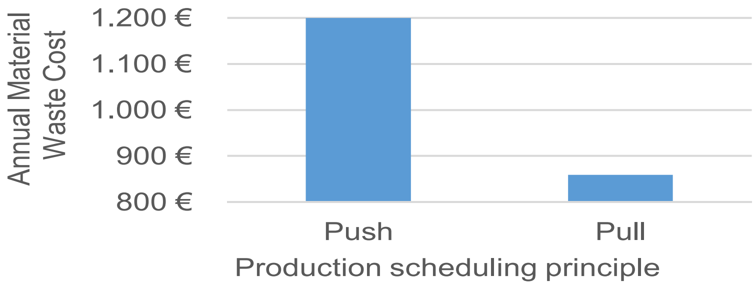



| Results (% Change) | | | | |
|---|---|---|---|---|
| Max Discommonality | Material cost efficiency | Average service-ability | Average through-put time | Other costs |
| 5 | 100,0% | 100,0% | 100,0% | 100,0% |
| 4 | 101,7% | 94,3% | 98,5% | 112,4% |
| 3 | 102,1% | 90,1% | 99,1% | 115,6% |

**Figure 62: Results of aroma-based product sequencing at filtration (Scenario 3)**

To reduce inventory deterioration, holding times are shortened by introducing pull-production in Scenario 4. Mash is only prepared to replenish finished goods stock. Currently distilleries plan their production based on raw material availability and price, rather than market need.

Due to raw fruit shortages at the time of finished goods depletion, a pull-based production leads to lower production volumes and higher production cost, as shown in Figure 63. While reducing the overall stock level and the instances of inventory deterioration, the overall profitability of the system suffered.




| Results (% Change) | | | | |
|---|---|---|---|---|
| Scheduling principle | Material cost efficiency | Average service-ability | Average through-put time | Other costs |
| Push | 100,0% | 100,0% | 100,0% | 100,0% |
| Pull | 139,7% | 95,3% | 69,5% | 177,4% |

**Figure 63: Results of pull-production (Scenario 4)**

After implementing stricter product sequencing rules at distilling, cost savings roughly 20% lower than the calculated result were attained.

## 8.3 Safety Glass Manufacturer

Sheet glass is cut, machined, tempered, and coated to make safety glass in a high-variety production.

**Step 1: Setting the system limits:** Factory management selects one process chain for the simulation study, encompassing glass scoring and breaking, drilling holes (machining), tempering, and coating the glass (see Figure 64).

**Step 2: Material sink description:** Large stock sheets of glass are scored and broken using a nesting software with bidirectional breaking in an automated process. Large stock sheets are restocked while others are discarded after processing. In the machining work center, holes and small geometries are drilled or cut and small amounts of cutting fluid are lost. In the tempering area, multiple glass plates are loaded in an oven, depending on the product mix and employee qualification, breakage occurs in varying quantities. Before coating, the plates are stocked in a semi-automated storage center, where may breakage occur. In the coating process, machine calibration (setup) requires iterative destructive testing and startup losses occur.

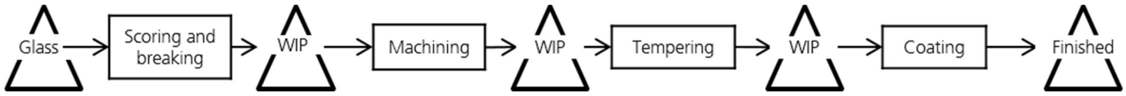


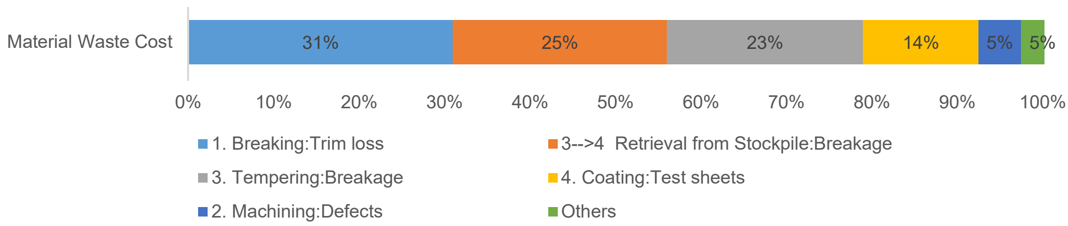

**Figure 64: Safety glass process chain**

Step 3: Measuring material waste at the material sinks:

Data on the product mixes and trim loss from stock sheets is extracted ERP system and cases of breakage from the shift protocols. The number of test sheets is logged for a time-period of 3 months.

**Table 28: Material waste forms for brandy production**

| Material sink | Waste form | Activity | % Material waste cost |
|---|---|---|---|
| 1. Breaking | Trim loss | Work | 31% |
| 1. Breaking | Defects | Work | 1% |
| 2. Machining | Defects | Work | 5% |
| 2. Machining | Chips, Cutting fluids | Work | 2% |
| 3. Tempering | Breakage | Work | 23% |
| 3-4 Retrieval from stockpile | Breakage | Transport loss | 25% |
| 4. Coating | Startup loss | Setup--> Work | 2% |
| 4. Coating | Defects | Work | 0% |
| 4. Coating | Test sheets | Setup--> Work | 12% |




**Regression analysis:** The waste amplifier measurement method from case study 1 is utilized (see Table 23). A regression analysis yielded a significant correlation between employee qualification and the number of breakage incidents per stock retrieval activity. Similarly, a correlation is seen between the number of iterative testing sheets consumed and part discommonality (see

Figure 65 left). As described in Section 6.4, a linear "product mix quality" scale is derived from ERP data (Figure 65 right).

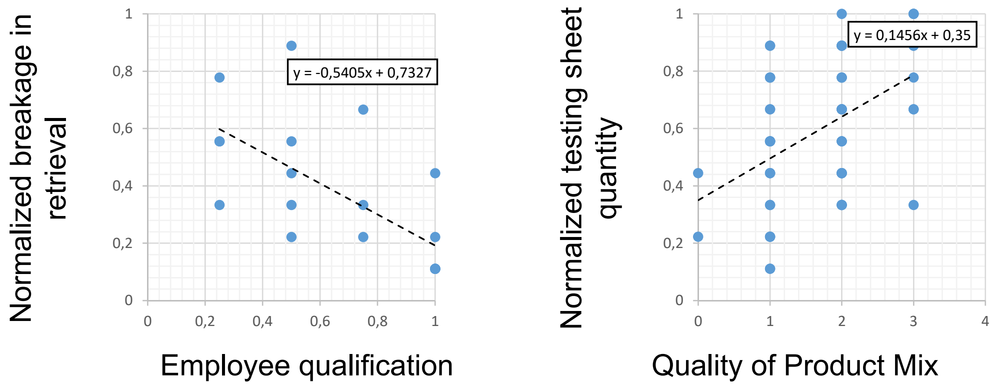



**Figure 65: Waste amplifiers in glass processing**

**Step 4: Parameterization of a simulation model**: The model is parameterized using the measured waste values per activity, the regression models, and the trim-loss / product mix model.

**Step 5: Verification of base line:** Following the parameterization the reference period (3 months) is simulated. To ensure the model reflected the cost and market performance of the real system, the average of 200 simulation runs is compared with static calculations based on measurement (see Figure 66).

| KPI | Simulation results* (% Static Calculation) |
|---|---|
| Volume | 120% |
| Throughput time | 94% |
| Waste cost | 92% |
| Other costs | 95% |

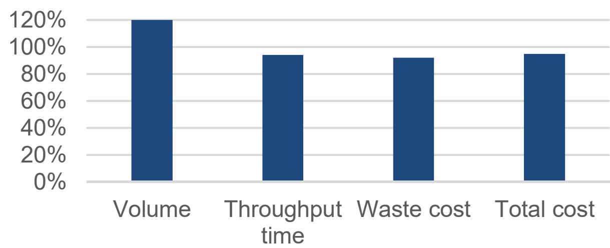



**Figure 66: Verification of glass processing model**

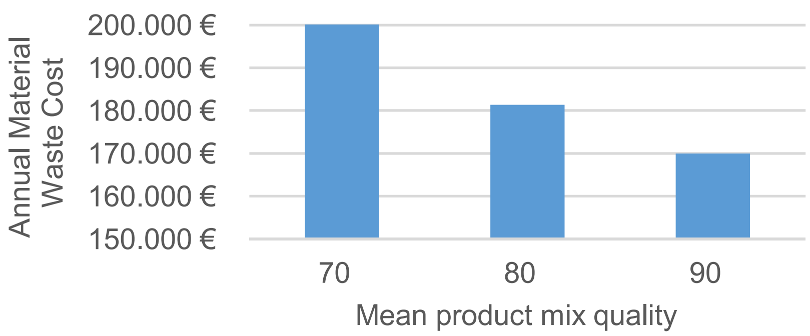
Step 6: Derivation of improvement measures and scenario creation:

Based on the most significant waste forms, the improvement measure generator suggested three scenarios, as shown in Table 29.

**Table 29: Simulated scenarios for glass processing**

| Improvement scenario | Addressed waste form | Parameter adjustment |
|---|---|---|
| 1. Product mix | Breaking: Trim loss | Preference for good product mixes at scoring and breaking |
| 2. Higher employee qualification in storage | Storage: Breakage | Higher employee qualification in material handling |
| 3. Product sequencing in coating | Coating: Test sheets, startup losses | Batch sequencing at coating by commonality |

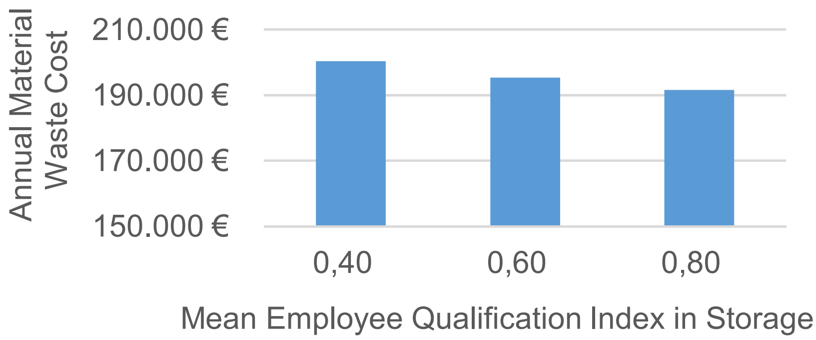
By giving preference to good product mixes at the breaking process, Scenario 1 is investigated in the simulation model in Figure 82. The restrictive product mixes lessened the serviceability, especially for customer-specific orders, which could not be shipped from stock. The stock levels to ensure utilization in breaking and downstream are slightly higher, resulting in a longer throughput time.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Average product mix quality | Material value efficiency | Average serviceability | Average throughput time | Other costs |
| 70% | 100,0% | 100,0% | 100,0% | 100,0% |
| 80% | 110,5% | 84,4% | 110,6% | 100,5% |
| 90% | 117,9% | 67,5% | 113,4% | 97,3% |

**Figure 67: Results of product mix quality variation (Scenario 1)**

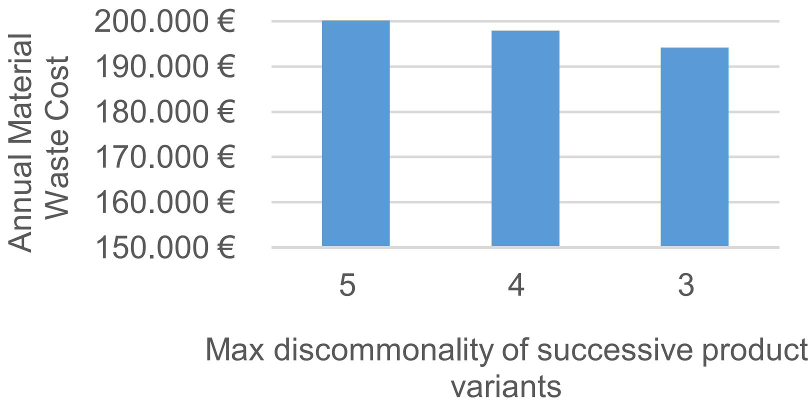
To reduce breakage of half-finished glass in handling activities, the employee qualification level of the responsible employee in the semi-automatic storage center is increased, yielding moderate cost savings, without any negative effects of system performance (compare Figure 68).




| Results (% base line) | | | | |
|---|---|---|---|---|
| Mean employee qualification index | Material cost efficiency | Average service-ability | Average throughput time | Other costs |
| 0,40 | 100,0% | 100,0% | 100,0% | 100,0% |
| 0,60 | 102,6% | 105,0% | 98,3% | 101,5% |
| 0,80 | 104,6% | 107,0% | 100,1% | 99,0% |

**Figure 68: Results of higher employee qualification in storage area (Scenario 2)**

Product sequencing in the coating process requires a higher scheduling effort and higher stock level to sequence coating batches, which in many cases differ from cutting or tempering batches. To investigate Scenario 3, the discommonality limit of successive batches is lowered, as shown in Figure 69. Due to the comparatively low raw material cost of glass test sheets, and the unavoidable minimum test sheet consumption per batch, the effects of the optimized product sequence are moderate.




| Results (% base line) | | | | |
|---|---|---|---|---|
| Max discommonality | Material cost efficiency | Average serviceability | Average throughput time | Other costs |
| 5 | 100,0% | 100,0% | 100,0% | 100,0% |
| 4 | 101,3% | 94,2% | 120,1% | 107,6% |
| 3 | 103,2% | 87,4% | 143,7% | 115,6% |

**Figure 69: Results of product sequencing at coating (Scenario 3)**

Comparing this case with the first case study, stronger regression coefficients with employee qualification are identified, indicating that employee qualification plays a larger role in material handling than in machine supervision in multiple machine operation. However, it is important to note that company-specific qualification scales are used in both studies. In larger studies, the use of an employee skills evaluation may yield more accuracy. The high regression coefficient for successive batch discommonality in tempering indicates that discommonality waste amplifier may have the largest effect on material waste in the setup process or immediately after the process, and less of an effect on subsequent activities. With more application cases, the selection of applicable waste amplifiers will be refined to reduce effort and reliance on process experts for input.

# 9 Critical Evaluation

In the following section, the fulfilment of the solution requirements is evaluated for the developed method. The results of the evaluation are summarized in Table 30.

**Savings potential:** The method calculates the change to total manufacturing costs and logistical KPI's for a specific improvement scenario. The method forgoes however optimization algorithms to parameterize improvement scenarios with minimal trade-offs, leaving the user to find the most favorable scenario through trial and error. Therefore, the developed method receives a 75% score.

**Goals conflicts:** The presented solution models a both material consumption costs, remaining manufacturing costs, and logistical KPIs, which are easily identifiable in the KPI Module (see Figure 80). However, this approach leaves the weighting of the cost and logistical goals to user, rather than defining a single performance index of the system to navigate goal conflicts.

**Fast and low effort:** The solution assumes that material waste can be swiftly allocated to a spatially isolated material sink driven by an operating logic. Particularly in assembly lines, where defects can be caused at any station and go unchecked, manufacturers struggle to identify the responsible station. If the assembly line is considered a single material sink, waste amplifiers like employee qualification lose their predictor power.

If the allocation is unclear, the time required to fulfill this prerequisite should not be underestimated. However, unlike the methods presented in the state of research, waste rate and waste quantity measurements for each material-machine-and product variant combination are only required for six operating states. Using the generic operating state logic allows a starting point for users without data on the exact operation of each material sink. The regression analysis is only performed for big-hitter waste forms and can generally be performed for quality defects using shift protocols without further data collection.

The computation time of the Vensim™ simulation model per scenario is under three minutes. However extending the model beyond the preexisting nine successive processes and more than five parallel machines per process requires code copying and trouble-shooting. The system-specific parameterization (process data, variant data) is performed in a spreadsheet.

**Fluctuating product spectrums:** The proposed regression analysis is recommended over a period with at least 60-120 production runs (10-20 observations x six waste amplifier variables). If the effect of waste amplifiers is neglected, the method can be applied to new product families using snapshot measurements.

**Process chains and relationships:** The supplier-customer relationships of the processes are modelled over the stockpiles in the system. Relationships via proximity are modelled over changes in ambient conditions (e.g. emitter process increases the air humidity in neighboring processes), although not relevant for the three cases studies.

**Multiple materials:** The simulation model accounts for up to nine waste flows per material sink. More waste flows can be added if necessary. Energy and non-material resource consumption (e.g. heating oil and cooling water in the distillery) are modelled only as an operating state-dependent cost.

**Dynamic behavior:** Both the classically simulated dynamics of the manufacturing system imposed by production schedules and disruptions in the form of breakdowns, employee absences, lowered yield as well as dynamics caused by waste production (e.g. changes in ambient conditions, and employee absence) are addressed with the method.

**All material consuming activities:** Operating state independent material consumption in peripheral activities and events can be used to account for most material consuming activities. Currently these must be assigned to a material sink and controlled by a pre-set or variable interval.

**Causality modelling:** the generic operating state logic supports companies in quickly identifying the correct logic. For operating-state-independent activities, it may be difficult to determine the causes leading to an occurrence and therefore difficult to define the activity intervals, e.g. modelling instances of employees discarding personal protective equipment.

**Table 30: Critical evaluation of presented solution**

| Body of Work | R1.Savings potential | R2. Goal conflicts | R3. Fast and low effort | R4. Fluctuating product spectrums | R5. Process chains and relationships | R6. Multiple materials | R7. Dynamic behavior | R8. All material consuming activities | R9. Causality modelling |
|---|---|---|---|---|---|---|---|---|---|
| Wohlgemuth et al. 2006<br>Junge 2007<br>Löfgren 2009<br>Greinacher et al. 2015 | ◔ | ◔ | ◕ | ◐ | ◔ | ◐ | ◔ | ◔ | ◔ |
| Heilala et al. 2008 | ◐ | ◐ | ◔ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |
| Duflou et al. 2012 | ◐ | ◐ | ○ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |
| Alvandi et al. 2015 | ◐ | ◐ | ◔ | ◔ | ◐ | ◔ | ◐ | ◐ | ◔ |
| Sheehan et al. 2016 | ◐ | ◕ | ◔ | ◔ | ◐ | ◕ | ◐ | ◕ | ◔ |
| Hopf 2016 | ◐ | ◐ | ◔ | ◔ | ◐ | ◐ | ◐ | ◐ | ◔ |
| **Sheehan 2017** | ◕ | ◕ | ◐ | ◐ | ◕ | ◕ | ◕ | ◕ | ◕ |

Overall, the solution addresses the identified solution requirements fairly well. Since the solution calculates manufacturing goal performance alongside material waste quantities and cost, information regarding goal conflicts and cost savings potential is readily available for decision makers. However, since no automated optimization component is present, the method relies on the user to diligently apply the systematic method and make reasonable assumptions to develop alternative scenarios for consideration.

The speed with which the method is applied in practice unfortunately cannot be truly described as fast or low effort. This weakness may be mitigated in the future by quicker data collection through the digitalization of the production system, or developing macros for quicker build up and parameterization of the model.

The large number of product-variant specific model parameters (e.g. defects measurement in work mode on milling machine) present a burden for firms with frequently fluctuating product spectrums, high product variety, or low product volumes. The current analysis of correlations between waste amplifiers and waste quantities require the collection of measurements under comparable conditions, which are difficult to guarantee if the measurements are scattered over a six-month period.

The model intends for only two types of process relationships, logistical (e.g. customer and supplier relationships) and spatial (those between neighboring machines). The extent with which the later relationship exists is only investigated as a change in local ambient conditions, indirectly leading to a change in material waste quantities. If the incorrect ambient conditions were investigated yielding no significant correlation, the relationship could be dismissed. In that respect the method relies strongly on the expertise of process experts, their understanding of the interdependencies within their manufacturing systems. In the future with readily available data, it may be possible to identify interdependencies in the factory facility without relying on expert input.

The solution models the material consumption as a function of pre-established machine operating states or peripheral, non-operating-state related consumption. The latter form can be used for any material waste form, even those not considered in Section 5, assuming the material waste can be assigned to a material sink and activity. In the future, methods that are more comprehensive may be able to detect and automatically allocate material waste to the appropriate material sinks and therefore this is accepted as a weakness of the method.

The solution utilizes continuous simulation with a variety of random functions to model dynamic behavior, though some of the dynamic behavior is neglected though the use of average material waste rates and average processing times. Digitalization of the data collection process reduces the effort associated with this phase and will allow users to build more dynamic behavior into the system.

# 10 Summary and Outlook

Section 1 establishes the purpose of this thesis, to present a solution for increasing material efficiency at the manufacturing system level. This purpose is reflected in the research question, "how can the material efficiency of a manufacturing system be increased without impeding other factory goals?"
Section 2 sets up the heuristic framework, presenting the understanding of industrial production and operations management (OM) and the use of materials in manufacturing systems. The framework is completed with the derivation of the metric, factory material efficiency, in Section 2.3.
With the framework of the problem established, Section 3 develops requirements for the solution to select the appropriate methodological approach. The business requirements stem from obstacles commonly faced by practitioners in the industry, based on the analysis of industry surveys. The complexity of the phenomenon of material waste in the factory is examined using the five W method to identify technical requirements. The comparison of four previously utilized methodological approaches yielded the selection of dynamic production simulation for further consideration.
In Section 4, existing bodies of work in the field of dynamic production simulation (the selection methodological approach) are evaluated based on the solution requirements to pinpoint the defects of the methods. The bodies of work are segmented into analysis methods, which collect data for simulation studies and scenario development, and synthesis methods that develop courses of action for improvement. The deficits, particularly the lack of consideration for the causality of diverse waste flows in a manufacturing system and the application of energy-efficiency-based approaches to material efficiency modelling are formulated into solution specifications.
In the pursuit of a model structure that accurately describes the causation of material waste, Section 5 investigates the causes of material waste through an

Ishikawa-analysis. The author then classifies the influence factors affecting material waste into four categories: those that increase the frequency of material-wasting activities, those that increase the duration of material-wasting activities, those, which link material waste to activities, and those, which increase the material waste quantity per activity. Because of this segmentation, the author investigates the relevance and completeness of modelling structures, e.g. machine operating states for material efficiency.

Based on the gained understanding of material waste causality, a model for material efficiency at the aggregate factory level is presented in Section 6, and the mechanisms for reducing total accumulated waste are demonstrated.

Finally, a holistic method for evaluating the effectiveness of material efficiency activities is presented in Section 7, based on system simulation, visualization, and systematic derivation of improvement measures. In Section 8, the developed solution in applied in three industrial settings. The first case describes the fabrication of aluminum components for automotive applications, where employee qualification, lot size, processing sequence, and the reaction time to tool breakage contribute to material efficiency. The second case study investigates the effect of product-sequence and holding time on material efficiency in a small brandy distillery. The third case examines the influence of employee qualification, product mix, and product sequence on waste at a safety glass manufacturer's facility.

A critical review evaluates the solution's fulfilment of the solution requirements in Section 9, describing persisting weaknesses in time-consuming data collection and reliance on expert input for interdependencies. Looking forward and beyond the focus of this work, with some adaptation alternative processing technologies could be evaluated using the same simulation method. However, the material waste data, which is measured or determined using historical data for existing production systems, would need to be estimated. Therefore, a research deficit remains in estimating the material consumption of future production systems, following strategic changes to a production system.

The method focuses on measures to limit the generation of material waste in mass or material waste cost. If a trade-off would occur in the system, with consequences equal in cost and material waste mass, but significantly different in environmental impact, the method regards both cases equally. Therefore, connecting the solution to a broader resource efficiency model would allow for multi-criterial decision-making.

For manufacturers close to the commodity markets in their vertical integration, expanding this method to include dynamic material pricing could synchronize the material demands of the production with availability on the markets.

To expand this method beyond the limits of the factory, including modelling transport conditions, more complex inventory shrinkage, or product failure in the field, significant adaptations to the method would need to be taken. However, for manufacturers who utilize rental, leasing, and operator business models, or those refurbishing goods in-house, an estimation of where material damage takes place and at what scale would allow for better forecasting of production, transport, and refurbishing operations.

As described in Section 9, the expansion of this method with automated data collection solutions and data analytics in the coming years will both reduce the effort for manufacturers and identify previously overlooked interdependencies of material waste in an industrial setting.

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## Appendix A: Model Implementation in Vensim™

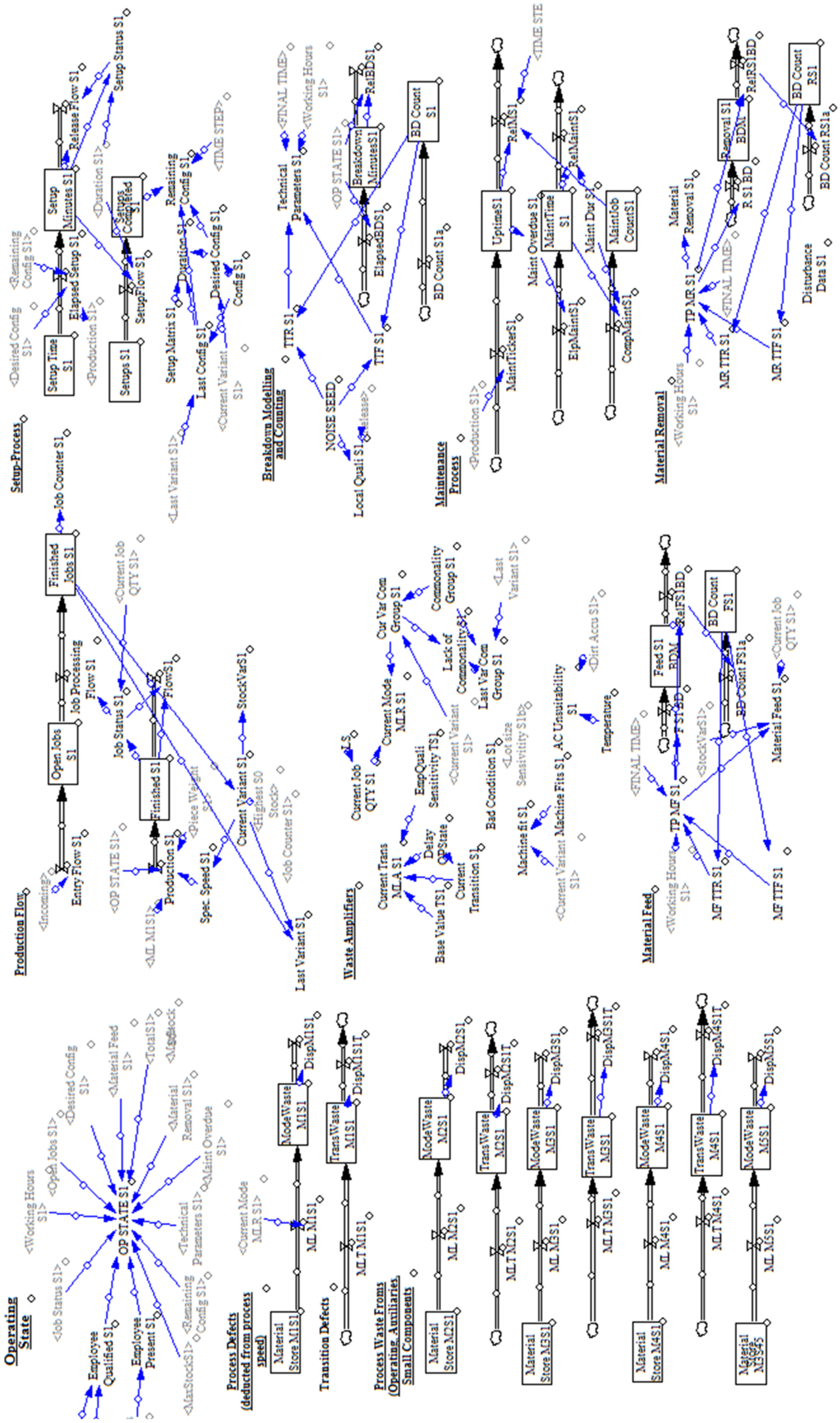
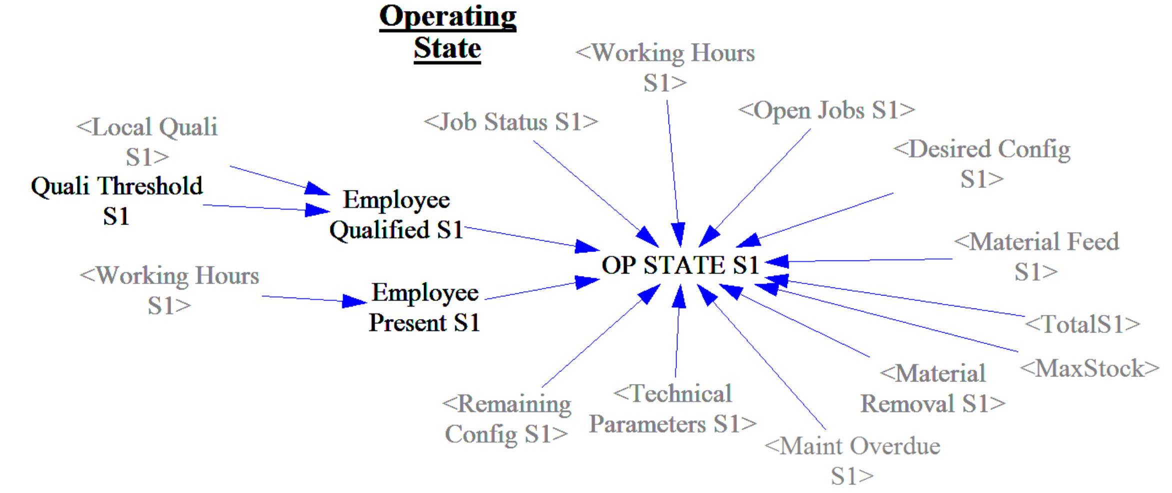
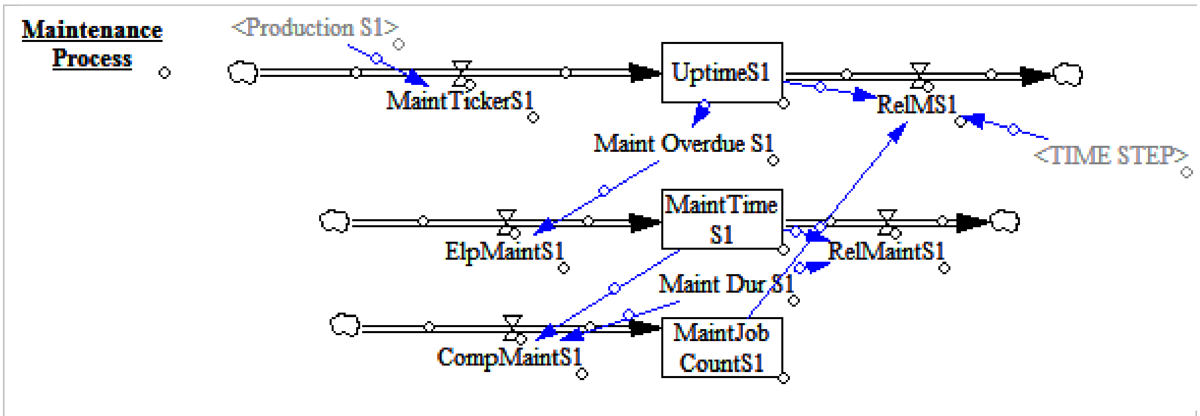



**Figure 70: Material sink module in Vensim™**



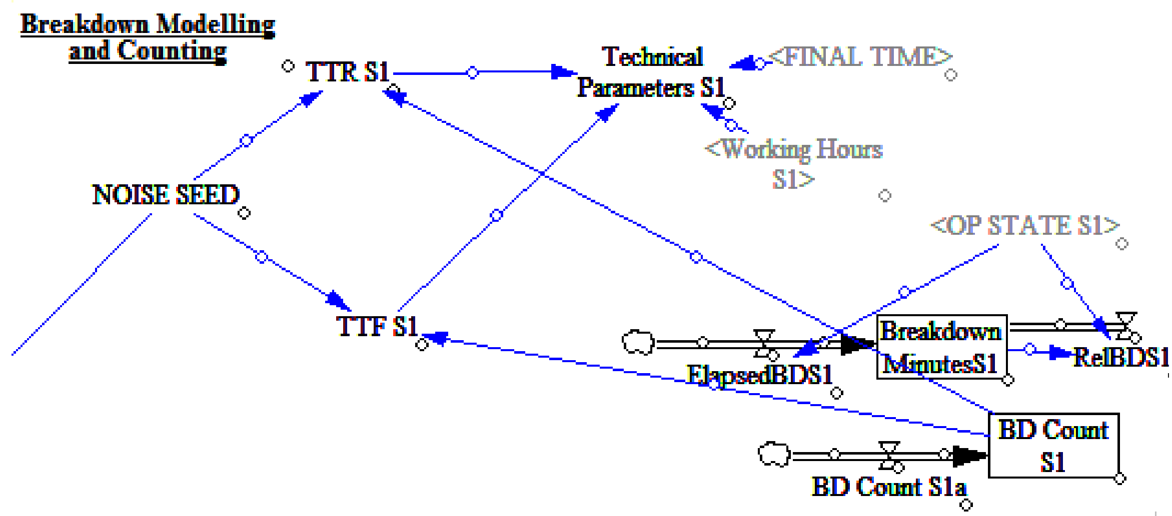

| Parameter | Description |
|---|---|
| Desired Config S1 | The required machine configuration for a given workpiece (from production order) |
| Employee Present S1 | Value 1 if employ present (random function used for bathroom breaks, etc.) |
| Local quali S1 | Qualification of current machine operator for machine S1 based on scale in skill matrix. |
| Maint Overdue S1 | Value 1 if time between maintenance activities is exceeded |
| Material Feed S1 | Value is 1 if the material feed is functioning |
| Material Removal S1 | Value is 1 if the material removal is functioning |
| MaxStock | Maximum allowed stock at downstream buffer, hinders further production |
| OP State S1 | Current operating state of material sink |
| Open Jobs S1 | Value is 1 if open jobs are in queue, otherwise 0 |
| Quali Threshold | Minimum value of Local Quali S1 required to bring machine into work state |
| Remaining Config S1 | The current machine configuration, changing value the moment a setup is complete |
| Technical Parameters S1 | Value 1 if the machine is in working order |
| TotalS1 | Current stock at the downstream buffer |
| Working Hours S1 | If the current time is inside the set working calendar the value is1, otherwise 0 |

**Figure 71: Parameters influencing operating state of one material sink in Vensim™**



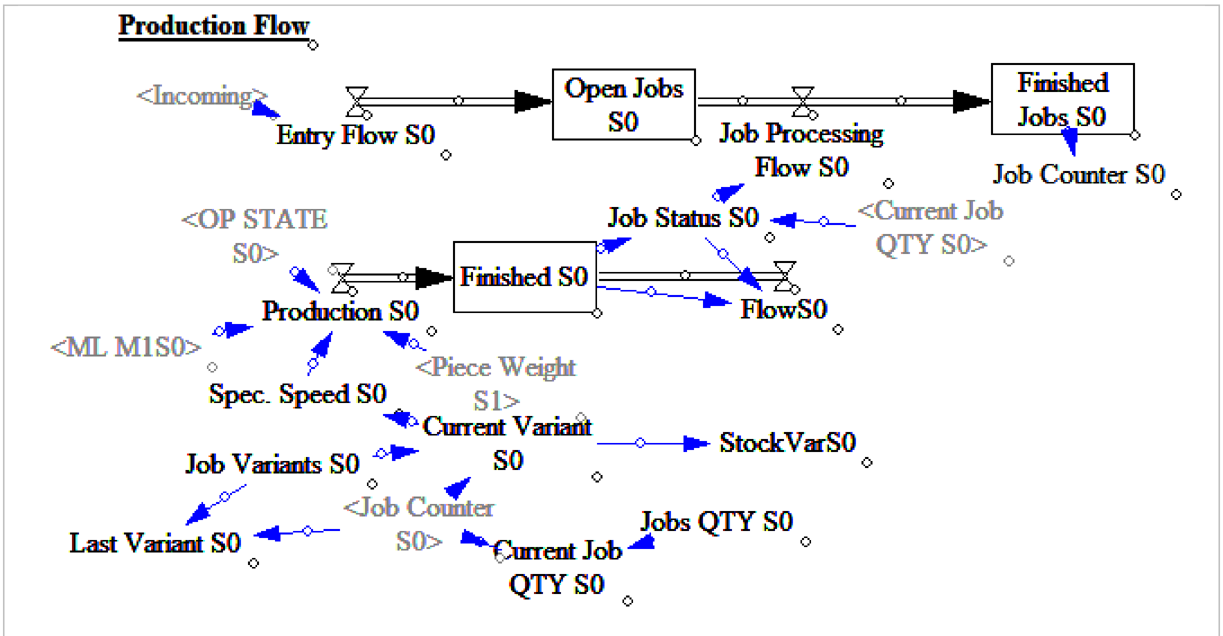

| Parameter | Description |
|---|---|
| CompMaintS1 | At the instance the maintenance is complete, the Value is 1, otherwise 0 |
| ElpMaintS1 | After receiving the signal from Maintenance Overdue S1, Value is 1 |
| Maint Overdue S1 | Value 1 if Uptime S1 exceeds the planned maintenance interval (not shown) |
| Maint Ticker S1 | Value 1 if machine is running |
| MaintDurS1 | The duration of a maintenance activity |
| MaintJobCount S1 | Counts completed maintenance jobs |
| MaintTime S1 | The count of the elapsed maintenance minutes (ElpMaintS1) |
| RelMaintS1 | Releases the counted uptime minutes when MaintTimeS1 exceeds the duration (MaintDur S1) |
| RelMS1 | Releases the counted uptime minutes at the time of maintenance completion |
| TIME STEP | The time interval of the simulation |
| Uptime S1 | Elapsed time in work state since last maintenance activity, is reset to 0 at the time of maintenance completion |

**Figure 72: Maintenance status in Vensim™**



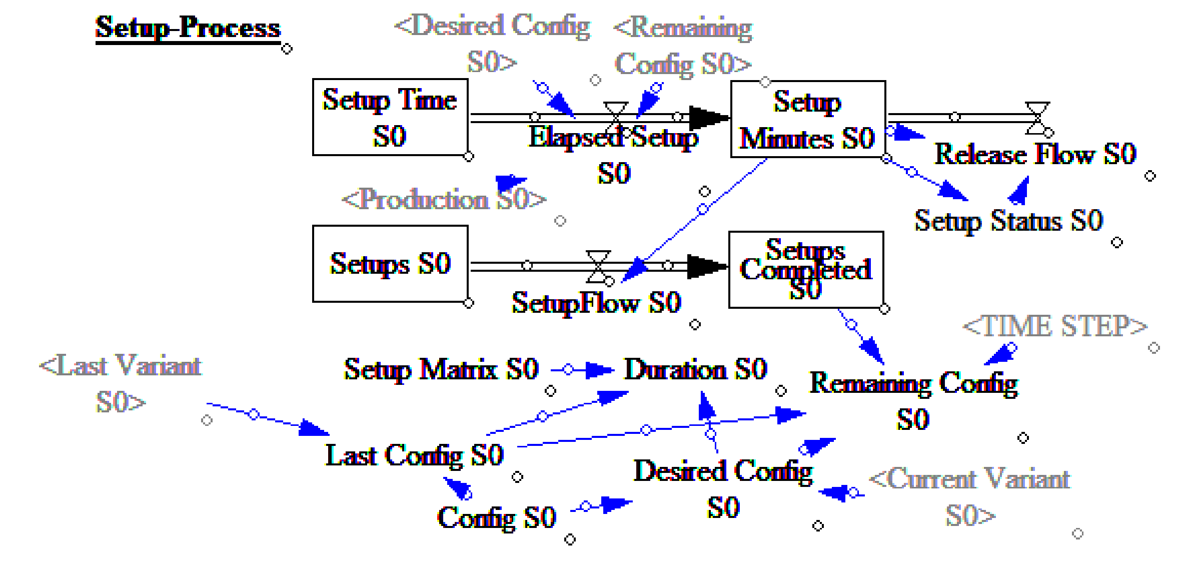

| Parameter | Description |
|---|---|
| BD Count S1 | The number of breakdowns that have occurred thus far. Comparing this value with its own value delayed by a time step sets new random values TTF S1 and TTR S1 |
| BD Count S1a | Value 1 in the instance a breakdown is resolved |
| Breakdown MinutesS1 | Count of the elapsed breakdown minutes (Elapsed BDS1) |
| Elapsed BDS1 | Value 1 an unresolved breakdown is open (Technical parameters =1) |
| Final Time | End time of the simulation |
| NOISE SEED | A Vensim™ parameter for calibrating a random function |
| OP State S1 | Current operating state of material sink |
| RelBDS1 | Resets breakdown minute count to 0 when they exceed TTR |
| Technical Parameters S1 | Pulsetrain function: Value 1 for a length of TTR S1 repeating in intervals of TTF S1 |
| TTF S1 | Elapsed time between breakdown incidents, a random function with unique value for each breakdown incident based on measured data |
| TTR S1 | Elapsed time between breakdown and machine repair, a random function with unique value for each breakdown incident based on measured data |
| Working Hours S1 | If the current time is inside the set working calendar the value is1, otherwise 0 |

**Figure 73: Breakdown modelling in Vensim™**



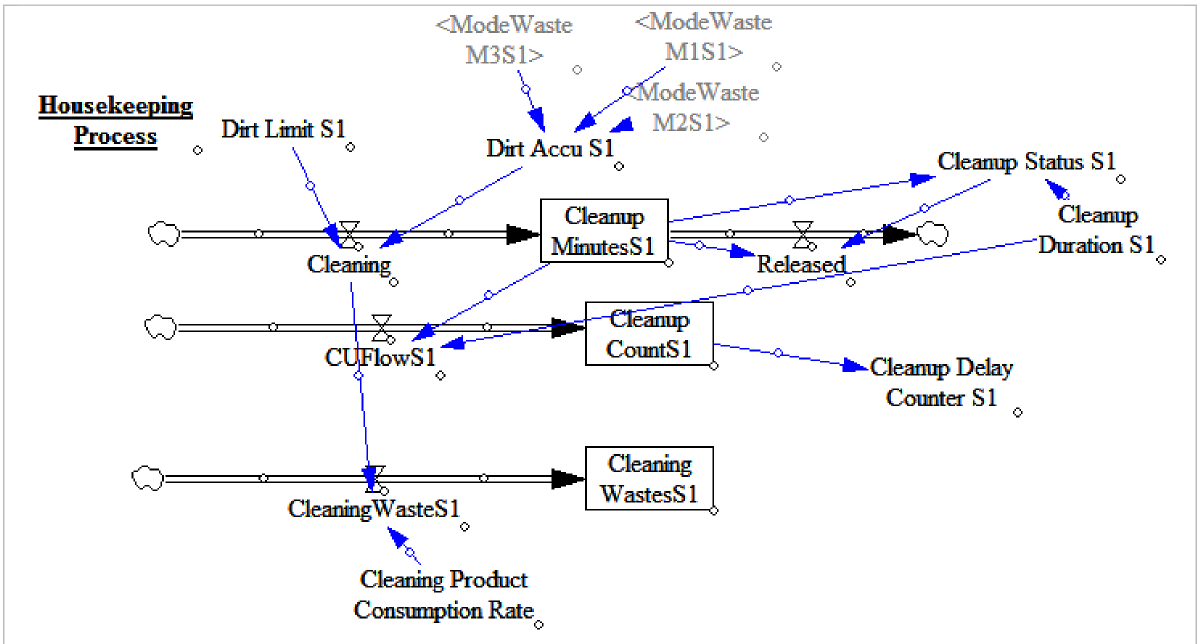

| Parameter | Description |
|---|---|
| Current Job QTY S1 | Number of pieces required for current job (read from schedule) |
| Current Job QTY S1 | The specified piece quantity for the current job |
| Current Mode MLR S1 | All material loss rates in this material sink for a current mode |
| Current Variant S1 | The current product variant |
| Entry Flow S1 | A flow of job orders entering this work station (material sink) |
| Finished Jobs S1 | The total completed jobs |
| Finished S1 | Good pieces for the current order |
| Flow S1 | Releases the good pieces and counts the order as completed |
| Incoming | A flow of orders entering the system as a whole |
| Job Counter S1 | The current job the material sink is working on in a schedule list |
| Job Processing Flow S1 | Value 1 in the instant a job is completed, otherwise 0 |
| Job Status S1 | Value 1 for the instant a job is completed, otherwise 0 |
| Job Variants S1 | List of all product variants in the schedule |
| Jobs QTY S1 | List of all piece quantities in the schedule |
| Last Variant S1 | The previous product variant on this machine |
| ML M1S1 | The rate of process defects occurring (kg/time step) |
| Open Jobs S1 | The number of jobs in the pipeline |
| Piece Weight S1 | The weight of a good workpiece (kg/piece) |
| Production S1 | The rate of good parts production (spec. speed minus MLM1S1) (pieces/time step) |
| Spec. Speed S1 | Production speed for product variant and machine combination |
| Stock VarS1 | The current downstream stock of this product variant |

**Figure 74: Operating-state-dependent production flow in Vensim™**



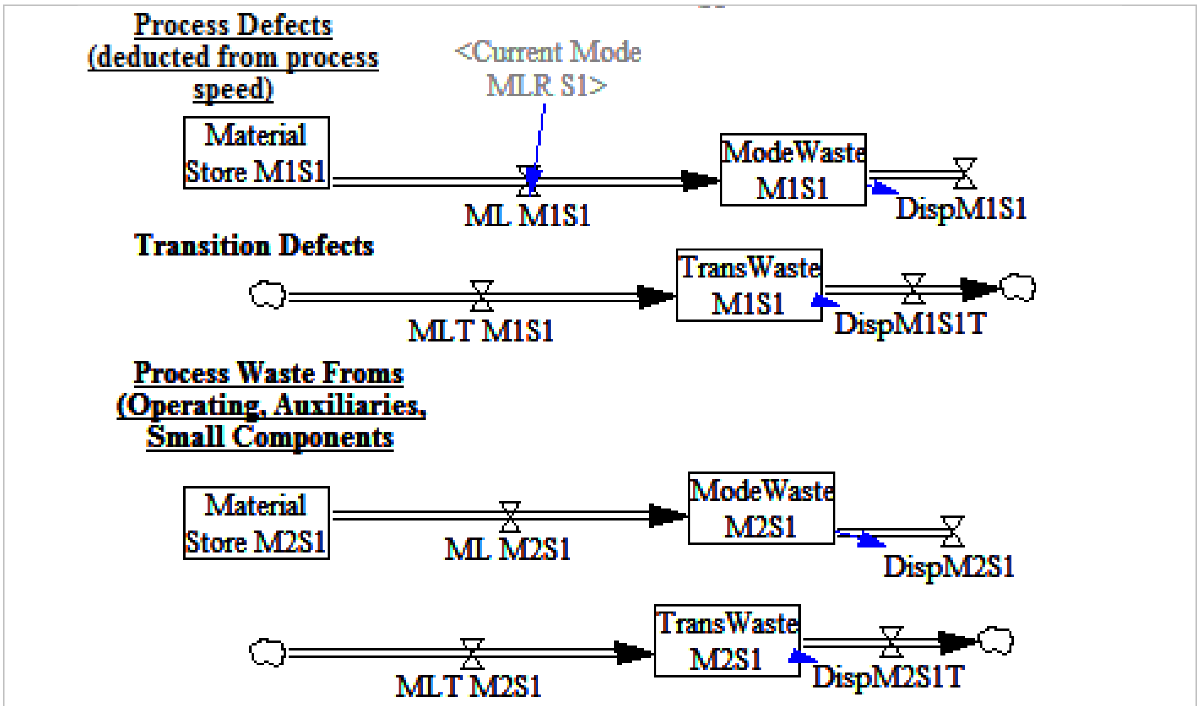

| Parameter | Description |
|---|---|
| Config S1 | List of machine configuration requirement for each product variant on machine S1 |
| Current Variant S1 | Current product variant |
| Desired Config S1 | The required machine configuration required for the current order |
| Duration S1 | The duration of the setup (unique random value for each incident) |
| Elapsed Setup S1 | Value 1 if setup is occurring |
| Last Variant S1 | Previous product variant |
| Production S1 | The rate with which good pieces are produced |
| Release Flow S1 | Resets the elapse setup minute count if Setup Minutes S1 exceeds the setup duration |
| Remaining Config S1 | The present configuration of the machine |
| Setup Flow S1 | Valu1 1 for the instant when setup complete |
| Setup Matrix S1 | Measured data on the typical duration range for each product variant sequence combination |
| Setup Minutes S1 | Count of the elapsed minutes since the setup activity started |
| Setup Status S1 | Signals when setup completed |
| Setup Time S1 | Maximum admissible time for all setup activities in a time period |
| Setups Completed S1 | Count of completed setup activities |
| Setups S1 | Maximum admissible number of setup activities |

**Figure 75: Machine set-ups in Vensim™**



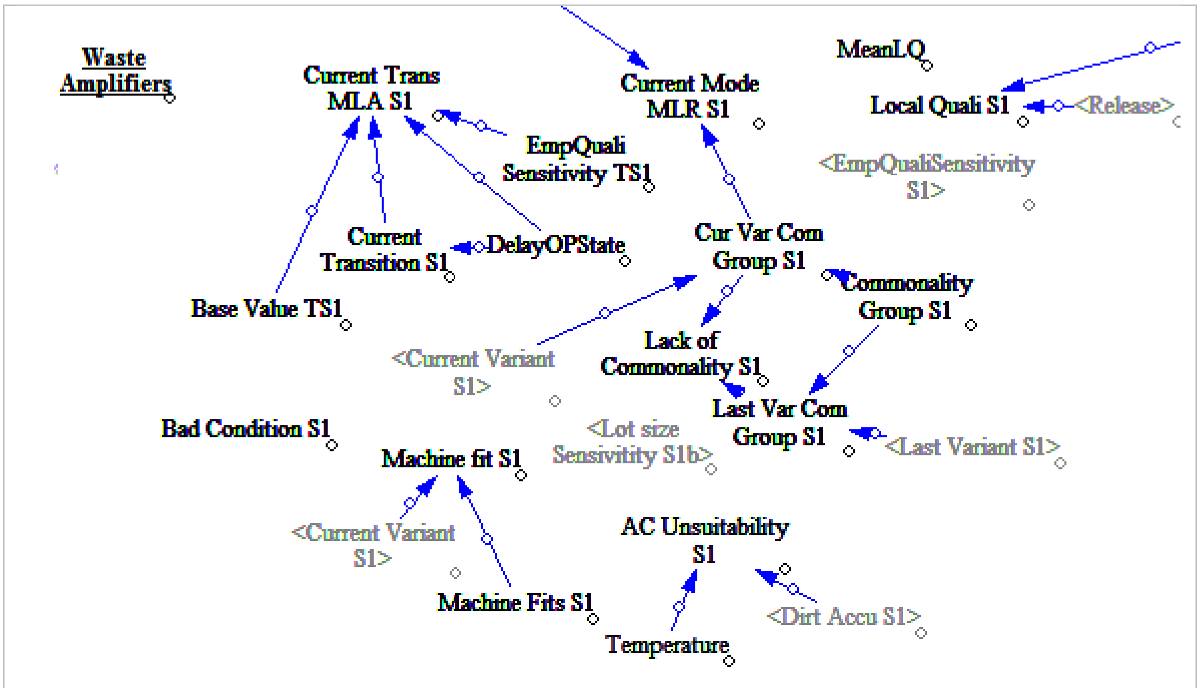

| Parameter | Description |
|---|---|
| Cleaning | Value 1 if dirt limit exceeded |
| Cleaning Product Consumption Rate | Employee dependent rate for cleaner consumption |
| Cleaning WastesS1 | Accumulated material cleaning waste in time period (kg) |
| CleaningWaste S1 | The rate with which cleaning waste accrues (kg/time step) |
| Cleanup Count S1 | Count of cleanups completed in time period |
| Cleanup Delay Counter S1 | Value of Cleanup Count S1 delayed one time step |
| Cleanup Duration | Parameter dependent cleanup duration |
| Cleanup Minutes S1 | The elapsed time in the current cleaning activity |
| Cleanup Status | Signals if cleanup complete |
| CUFlow S1 | Value 1 for the instant when cleanup completed, 0 otherwise |
| Dirt Accu S1 | Accumulated dirt (partially function of waste) |
| Dirt limit S1 | Maximum admissible dirt in the peripheral area |
| ModeWasteMXS1 | Material waste quantity not yet cleaned away |
| Released | Releases elapsed time count at completion |

**Figure 76: Example peripheral process Vensim™**




| Parameter | Description |
|---|---|
| Current Mode MLR S1 | Vector of all material waste rates |
| DispMXS1 | The rate of disposal of material waste (clearing it from vicinity) |
| Material Store MXS1 | The material stock of any starting material (x) |
| ML M1S1 | Material waste rate for process defects (deducted from production rate) |
| ML MXS1 | The material waste rate of a non-process defect waste form |
| MLT MXS1 | Rate of material waste occurring through operating state transitions, taking on a non-zero value representing the quantity for one timestep per incident |
| ModeWaste MXS1 | The accumulated material waste currently in the material sink vicinity for each material waste form (x) |
| TransWaste M1S1 | Accumulated waste from transitions in the vicinity |
| Current Mode MLR S1 | Vector of all material waste rates |

**Figure 77: Accumulated material waste in a material sink in Vensim™**




| Parameter | Description |
|---|---|
| AC Unsuitability | Degree of unsuitability of ambient conditions |
| Bad Condition S1 | Condition of machine |
| Base Value TS1 | Constant from regression model representing the waste quantity per incident in the absence of all amplifiers |
| Commonality Group S1 | List of groups of product variants with common characteristics |
| Cur Var Com Group S1 | Name of group sharing similar product variant specific characteristics with current product variant |
| Current Mode MLR | Vector of material waste forms linked with operating states |
| Current Trans MLA S1 | Vector of material waste forms linked with transitions |
| Current Transition S1 | Number of current operating state transition in a list of possible combinations |
| Current Variant S1 | Current product variant |
| DelayOPState | Value of operating state delayed one time step |
| Emp Quali Sensitivity S1 | Vector of coefficient from regression model for employee qualification for waste caused by operating states |
| Emp Quali Sensitivity TS1 | Vector of coefficient from regression model for employee qualification for waste caused by operating state transitions |
| Lack of Commonality S1 | Compares the commonality groups of the current and last product variants |
| Local Quali S1 | Current employee qualification |
| Machine fit S1 | Compatibility of current product variant and machine |
| Machine Fits S1 | List of machine/product variant compatibilities |
| Temperature | Current ambient temperature |

**Figure 78: Waste amplifiers in Vensim™**

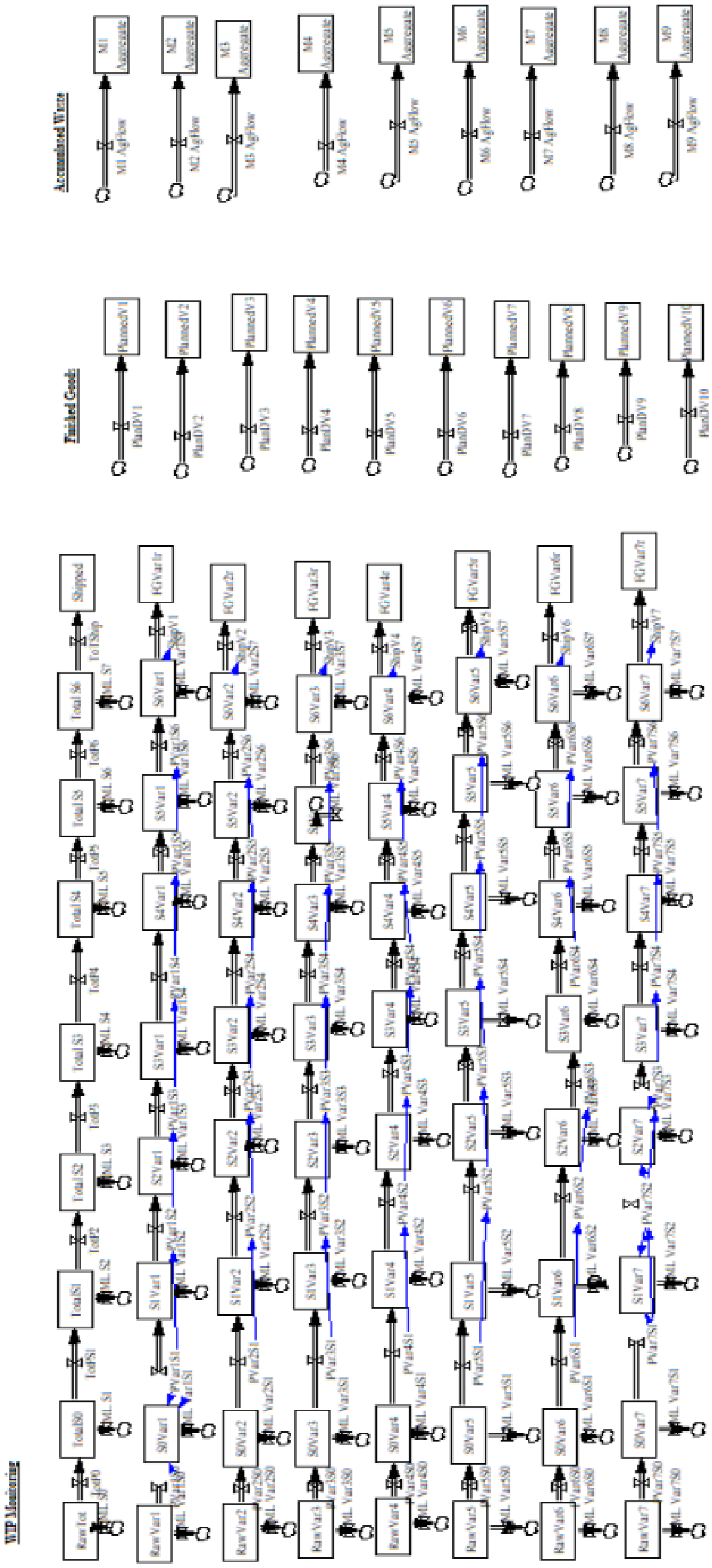



**Figure 79: Material management module in Vensim™**

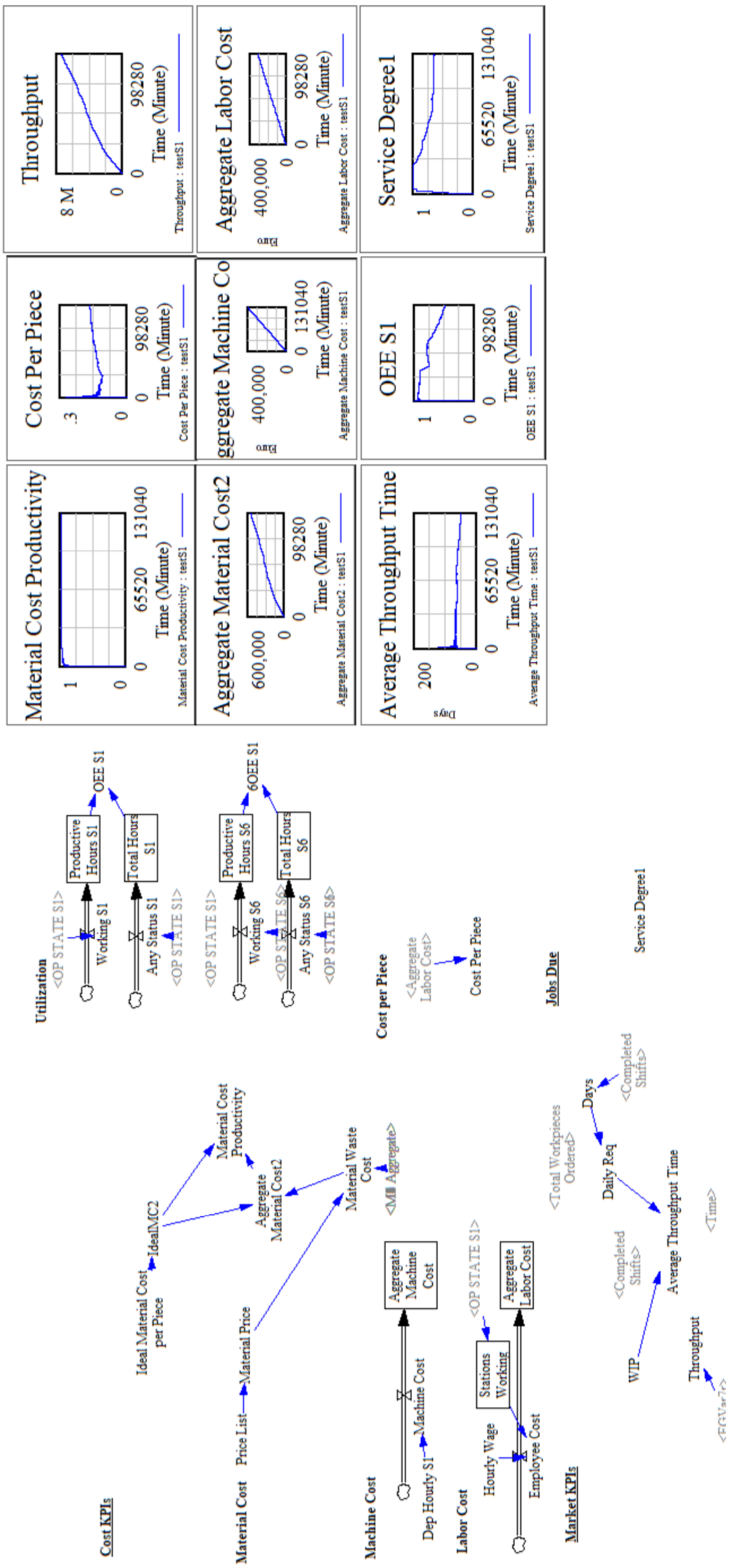



**Figure 80: KPI module in Vensim™**

# Appendix B: Input Tables for Simulation Model

| Job Number S2 | Variant | QTY | Sum | Setup Type | Plan Run Ti | Setup Dura | Config |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 7000 | 140,0416667 | | 140 | 20 | 2 |
| 2 | 2 | 7000 | 140 | 2,02 | 140 | 0 | 2 |
| 3 | 3 | 7000 | 140 | 2,03 | 140 | 0 | 3 |
| 4 | 3 | 7000 | 140 | 3,03 | 140 | 0 | 3 |
| 5 | 1 | 7000 | 140 | 3,01 | 140 | 0 | 1 |
| 6 | 3 | 7000 | 280 | 1,03 | 140 | 0 | 3 |
| 7 | 3 | 7000 | 420 | 3,03 | 140 | 0 | 3 |
| 8 | 2 | 7000 | 560 | 3,02 | 140 | 0 | 2 |
| 9 | 3 | 7000 | 0 | 2,03 | 140 | 0 | 3 |
| 10 | 1 | 7000 | 140 | 3,01 | 140 | 0 | 1 |
| 11 | 1 | 7000 | 280 | 1,01 | 140 | 0 | 1 |
| 12 | 2 | 7000 | 420 | 1,02 | 140 | 0 | 2 |
| 13 | 1 | 7000 | 560 | 2,01 | 140 | 0 | 1 |
| 14 | 2 | 7000 | 0 | 1,02 | 140 | 0 | 2 |
| 15 | 1 | 7000 | 140 | 2,01 | 140 | 0 | 1 |
| 16 | 2 | 7000 | 280 | 1,02 | 140 | 0 | 2 |
| 17 | 1 | 7000 | 420 | 2,01 | 140 | 0 | 1 |
| 18 | 2 | 7000 | 560 | 1,02 | 140 | 0 | 2 |
| 19 | 3 | 7000 | 0 | 2,03 | 140 | 0 | 3 |
| 20 | 3 | 7000 | 140 | 3,03 | 140 | 0 | 3 |
| 21 | 1 | 7000 | 280 | 3,01 | 140 | 0 | 1 |
| 22 | 3 | 7000 | 420 | 1,03 | 140 | 0 | 3 |
| 23 | 3 | 7000 | 560 | 3,03 | 140 | 0 | 3 |
| 24 | 3 | 7000 | 0 | 3,03 | 140 | 0 | 3 |
| 25 | 3 | 7000 | 140 | 3,03 | 140 | 0 | 3 |
| 26 | 1 | 7000 | 280 | 3,01 | 140 | 0 | 1 |

JobDataS2 | VariantDataS2 | SetupMatrixS2 | WasteS2 | TransWasteS2 | DisturbanceData

**Figure 81: Job schedule input table for process module**

| Variant | Pieces/Minutes | Config | Commonality Group | Unsuitability | Required Quali |
|---|---|---|---|---|---|
| 1 | 50 | 1 | 1 | 1 | 2 |
| 2 | 50 | 2 | 1 | 1 | 2 |
| 3 | 50 | 3 | 1 | 1 | 2 |
| 4 | 50 | 4 | 1 | 1 | 2 |
| 5 | 50 | 5 | 1 | 1 | 2 |
| 6 | 50 | 6 | 1 | 1 | 2 |
| 7 | 50 | 7 | 1 | 1 | 2 |
| 8 | 50 | 8 | 1 | 1 | 2 |
| 9 | 50 | 9 | 1 | 1 | 2 |
| 10 | 50 | 10 | 1 | 1 | 2 |
| 11 | 50 | 11 | 1 | 1 | 2 |
| 12 | 50 | 12 | 1 | 1 | 2 |
| 13 | 50 | 13 | 1 | 1 | 2 |
| 14 | 50 | 14 | 1 | 1 | 2 |
| 15 | 50 | 15 | 1 | 1 | 2 |

JobDataS2 | VariantDataS2 | SetupMatrixS2 | WasteS2 | TransWasteS2 | DisturbanceData

**Figure 82: Process-specific product variant data input table**

# Appendix C: Overview of Improvement Measure Generator

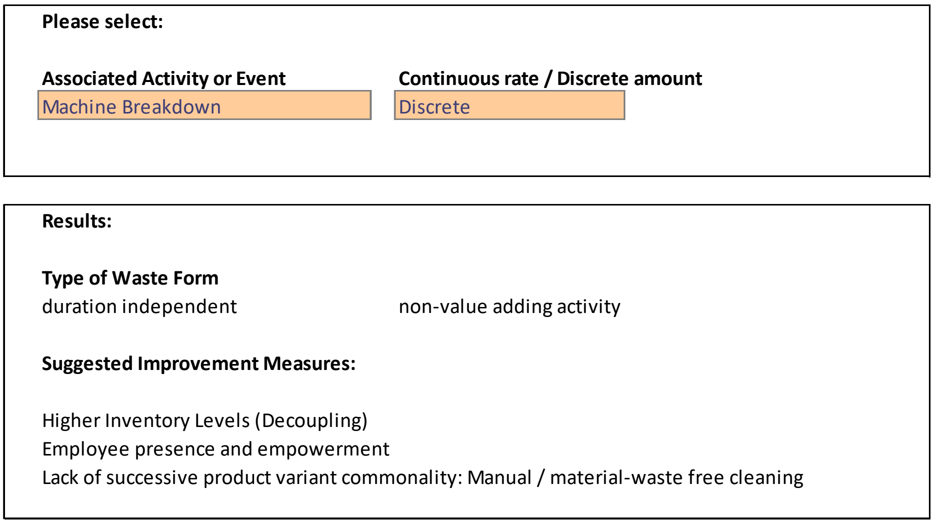



**Figure 83: Interface of improvement measure generator**

**Table 31: Library of improvement measures**

| Improvement Measure | Mechanism | Activity type | Applicable Activities | Material type |
|---|---|---|---|---|
| Defect avoidance | Avoid Activity Occurrence | any | Processing | any |
| Avoiding overproduction | Avoid Activity Occurrence | any | Processing | any |
| Better utilization of batch containers (e.g. paint racks) | Avoid Activity Occurrence | any | Processing | any |
| Larger stock units (e.g. longer coils) | Avoid Activity Occurrence | any | Stock Material Unit Replenishment Interval | any |
| Bundling orders/larger lots | Avoid Activity Occurrence | any | Set-up | any |
| Bundling activities | Avoid Activity Occurrence | any | Maintenance | any |
| Immediately processing/ Inventory reduction | Avoid Activity Occurrence | any | Storage | any |
| Loading more pieces on vehicles | Avoid Activity Occurrence | any | Transport/ Handling | any |
| Avoiding excessive handling | Avoid Activity Occurrence | any | Transport/ Handling | any |
| Avoiding Overproduction | Avoid Activity Occurrence | any | Destructive Testing | any |
| Prevent spills and messes | Avoid Activity Occurrence | any | Housekeeping | any |
| Clean only at management designated times | Avoid Activity Occurrence | any | Housekeeping | any |
| More frequent preventative maintenance | Avoid Activity Occurrence | any | Machine Breakdown | any |
| Reduced loading | Avoid Activity Occurrence | any | Machine Breakdown | any |
| Higher inventory levels (Decoupling) | Avoid Activity Occurrence | any | Machine Idling | any |
| Preventative maintenance on feeder technologies | Avoid Activity Occurrence | any | Machine Idling | any |
| Employee awareness training | Avoid Activity Occurrence | any | Machine Idling | any |
| Limit holding times | Avoid Activity Occurrence | any | Material Aging | any |
| Employee qualification | Avoid Activity Occurrence | any | Material Aging | any |
| Employee awareness and safety training | Avoid Activity Occurrence | any | Transport/ Handling | any |
| Assignment to the fastest machine | Activity Duration | duration-dependent | Processing | any |
| SMED | Activity Duration | duration-dependent | Set-up | any |

| Improvement Measure | Mechanism | Activity type | Applicable Activities | Material type |
|---|---|---|---|---|
| Process optimization | Activity Duration | duration-dependent | Planned maintenance | any |
| Mean time to repair reduction | Activity Duration | duration-dependent | Machine breakdown | any |
| Mean time to repair reduction for feeder and removal technology | Activity Duration | duration-dependent | Machine idling | any |
| Employee presence and empowerment | Activity Duration | duration-dependent | Machine idling | any |
| Forgoing consumption by adjusting process specifications (e.g. dry-machining,) | Delinkage | any | Processing | operating material |
| Forgoing consumption through organizational changes (e.g. intermediate packaging) | Delinkage | any | Handling | operating material |
| Turning off unneeded, waste-causing modules in inactive periods | Delinkage | any | Set-up | operating material |
| Turning off unneeded, waste-causing modules in inactive periods | Delinkage | any | Planned maintenance | operating material |
| Turning off unneeded, waste-causing modules in inactive periods | Delinkage | any | Machine Idling | operating material |
| Turning off unneeded, waste-causing modules in inactive periods | Delinkage | any | Machine Breakdown | operating material |
| Lack of successive product variant commonality: Residue prevention | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Barrier mechanisms (coatings) | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Manual / material-waste free cleaning | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Accelerating process restabilization | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Technical measures | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Preventing employee confusion | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Poka yoke mechanisms | Amplifier Control | any | any | any |
| Lack of successive product variant commonality: Employee training | Amplifier Control | any | any | any |
| Advanced equipment age: Preventative maintenance activities | Amplifier Control | any | any | any |
| Large lot sizes: Process monitoring and parameter adjustment | Amplifier Control | any | any | any |
| Low employee qualification: Increase process automation | Amplifier Control | any | any | any |
| Out-of-range ambient conditions: Enclose processes | Amplifier Control | any | any | any |

| Improvement Measure | Mechanism | Activity type | Applicable Activities | Material type |
|---|---|---|---|---|
| Lack of successive product variant commonality: Product standardization, modularization | Amplifier Desensitization | any | any | any |
| Lack of successive product variant commonality: Campaigns/ bundling batches with high commonality | Amplifier Desensitization | any | any | any |
| Lack of successive product variant commonality: Segmentation: assigning uncommon product variants to opposing machines | Amplifier Desensitization | any | any | any |
| Unsuitability of machine / product variant combination: Segmentation: assigning product variants only to the most suitable machine | Amplifier Desensitization | any | any | any |
| Unsuitability of machine / product variant combination: Prioritization: giving first priority to orders with exclusive suitability in machine queues | Amplifier Desensitization | any | any | any |
| Unsuitability of machine / product variant combination: Product simplification | Amplifier Desensitization | any | any | any |
| Unsuitability of machine / product variant combination: Machine universality | Amplifier Desensitization | any | any | any |
| Advanced equipment age: Investment in new machines | Amplifier Desensitization | any | any | any |
| Advanced equipment age: Prioritize utilization of newer machines | Amplifier Desensitization | any | any | any |
| Large lot sizes: Run small lots | Amplifier Desensitization | any | any | any |
| Low employee qualification: Train Employees | Amplifier Desensitization | any | any | any |
| Out-of-range ambient conditions: Controlling and Containing Ambient Conditions | Amplifier Desensitization | any | any | any |
| Out-of-range ambient conditions: Producing only robust-product variants in periods of undesirable ambient conditions | Amplifier Desensitization | any | any | any |

To enable manufacturers to select the best-suited instruments for holistic material efficiency, this thesis presents a simulation-based method, modelling the causality of material waste parallel to manufacturing performance. The developed procedure begins with a current state survey to examine the relation between material waste and activities of the factory. A systematic method allows the user to generate a list of improvement scenarios. A dynamic simulation investigates the effectiveness of the improvement measures (system dynamics).

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