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Development of Material Flow Cost Accounting and Value Added Statements as Planning Instruments for Sustainability Management

Dissertation

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Abstract

In companies, the environmental and social objectives of employees, society, and customers have become in relation to the primary economic goals of the equity holders more important. The partially contrary relationships of these goal categories cause different short- and long-term stakeholder conflicts, which are in the responsibility of sustainability management. For the alignment of the all activities of a company on its sustainability goals, sustainability management requires consistent planning information. But due to the shareholder value orientation that mostly dominated in companies in the past decades, suitable economic-environmental as well as economic-social controlling tools that provide planning information in an appropriate way rarely exist until now. Therefore, the development of suitable planning instruments for corporate decision-making and behavioral control in sustainability management is necessary. Controlling tools that possess for this purpose a great potential are material flow cost accounting and value added statements. For this reason, the further development of these instruments and their application in sustainability management is subject of this dissertation.

With the development of differentiated material flow models succeeds the production theory-based foundation of material flow cost accounting, which enable the calculation of the material and product demand of a company in consideration of waste, rejects, reworking, and recycling. After the determination of the material demand of the products and the material losses, the transformation processes of a company are investigated on quantity center level. The efficient, inefficient, and inefficiency-decreasing material flows are analyzed with material- and product-oriented inputoutput tables. The material flows are subsequently allocated on the basis of differentiated allocation rates to the products of a company. On the basis of the material flow models appears the conception of a planning material flow cost accounting system, which is designed as a full cost accounting tool. For this purpose, the major assumption of this cost accounting system and its structure are discussed. Afterwards, the cost drivers of the manufacturing, recycling, and disposal quantity centers are identified and the budgeting process of the quantity center costs is explained in detail. Besides the budgeting of the primary costs, the dissertation pays attention on the treatment of the secondary costs in the material flow cost matrix. In cost unit accounting, the quantity center costs are allocated with cost allocation rates to the material flows of the products and material losses. For this purpose, meaningful product-, quantity center-, and inefficiency factor-oriented cost calculation schemes are developed.

The conceptual development of a value added-oriented valuation approach base on the creation of planned value added statements. The future value added of a company is forecasted on the basis of a differentiated value driver model and future-oriented value added statements on cash flows. The calculation of the future value added creation and distribution is subsequently expanded from a single to an infinite forecast horizon. With the determination of the market value of the future value added and the market values of the employees, the society, the equity holders, and debt holders future successes, the conception of the valuation approach succeeds that is denoted as discounted value added approach. Afterwards, the application of the value added-oriented valuation approach in sustainability management is described as well as the stakeholder value and the market values of the stakeholders' successes are analyzed in more detail. The section concludes with the development of value added- and stakeholder-oriented key ratios that can be used in sustainability management for corporate decision-making and behavioral control.

Zusammenfassung

In Unternehmen haben die ökologischen und sozialen Ziele der Mitarbeiter, der Gesellschaft und der Kunden gegenüber den primär ökonomischen Interessen der Eigenkapitalgeber zunehmend an Bedeutung gewonnen. Die aus den z.T. konträren Beziehungen dieser Zielkategorien resultierenden kurz- und langfristigen Interessenkonflikte fallen in den Verantwortungsbereich des Nachhaltigkeitsmanagements. Um die Aktivitäten eines Unternehmens auf dessen Nachhaltigkeitsziele auszurichten bedarf es im Nachhaltigkeitsmanagement jedoch konsistenter Planungsinformationen. Aufgrund der in den vergangenen Jahrzehnten in Unternehmen vielfach dominierenden Shareholder Value Orientierung existieren allerdings bislang kaum geeignete ökonomisch-ökologische bzw. ökonomisch-soziale Planungsinstrumente. Hieraus resultiert die Notwendigkeit der Entwicklung geeigneter Controllinginstrumente, die zur Entscheidungsfindung und Verhaltenssteuerung im Nachhaltigkeitsmanagement verwendet werden können. Als grundsätzlich für diesen Zweck geeignete erscheinen die Materialflusskostenrechnung und die Wertschöpfungsrechnung, deren konzeptuelle Weiterentwicklungen und Anwendung im Nachhaltigkeitsmanagement Gegenstand der vorliegenden Dissertation sind.

Mit der Entwicklung von differenzierten Materialflussmodellen erfolgt eine produktionstheoretische Fundierung der Materialflusskostenrechnung. Diese ermöglicht die Planung des Material- und Produktbedarfs eines Unternehmens unter der Berücksichtigung von Abfall, Ausschuss, Nacharbeit und Recycling. Nach Ermittlung des Materialgesamtbedarfs der Produkte und Materialverluste erfolgt auf Mengenstellenebene eine differenzierte Analyse der Transformationsprozesse. Hierbei werden mit Hilfe von produkt- sowie materialorientieren Inputoutput Tabellen die effizienten, ineffizienten und ineffizienzmindernden Materialflüsse analysiert. Die Materialflüsse werden anschließend auf Basis von differenzierten Zuschlagssätzen den Produkten des Unternehmens zu geschlüsselt. Hierauf aufbauend erfolgt die Konzeption eines planungsbasierten Materialflusskostenrechnungssystems auf Vollkostenbasis. Hierfür werden in einem ersten Schritt dessen zentrale Annahmen und der strukturelle Aufbau dargestellt. Anschließend werden die Kostentreiber der Fertigungs-, Recycling- und Entsorgungsmengenstellenkosten identifiziert sowie deren Planung im Detail erörtert. Neben der Planung der primären Kosten wird hierbei auch auf die Behandlung der Sekundärkosten in der Materialflusskostenmatrix eingegangen. In der Kostenträgerrechnung werden die Mengenstellenkosten mit Hilfe

von Zuschlagssätzen den Materialflüssen der Produkte und Materialverluste differenziert zugeordnet. Für diesen Zweck werden zudem aussagekräftige produkt-, mengenstellen- und ineffizienzfaktororientierte Kostenkalkulationsschemata entwickelt.

Die konzeptuelle Entwicklung eines wertschöpfungsorientierten Bewertungsverfahrens basiert auf der Erstellung planungsbasierter Wertschöpfungsrechnungen. Die zukünftige Entstehung und Verteilung der Wertschöpfung wird hierbei mit Hilfe eines differenzierten Werttreibermodells und zukunftsorientierten Wertschöpfungsrechnungen auf der Basis von Zahlungen ermittelt. Die Planung der Entstehung und Verteilung der Wertschöpfung wird anschließend von einem einperiodigen Kontext auf einen unendlichen Planungshorizont ausgeweitet. Mit der Ermittlung des Marktwerts der zukünftigen Wertschöpfung sowie der Marktwerte der Erfolge der Mitarbeiter, der Gesellschaft, der Eigenkapitalgeber und Fremdkapitalgeber erfolgt die eigentliche Konzeption des als Discounted Value Added Approaches bezeichneten Bewertungsverfahrens. Anschließend wird die Anwendung des wertschöpfungsorientierten Bewertungsansatzes im Nachhaltigkeitsmanagement beschrieben sowie die Entstehung und Verteilung des Stakeholder Value tiefergehend analysiert. Abschließend werden wertschöpfungs- und stakeholderorientierter Kennzahlen zur Entscheidungsfindung und Verhaltenssteuerung im Nachhaltigkeitsmanagement abgeleitet.

Table of Content

List of Abbreviations

ISO	International Organization for Standardization
MDK	Material Distribution Key
MFCA	Material Flow Cost Accounting
SASB	Sustainability Accounting Standard Board

List of Figures

List of Tables

1. Introduction

1.1 Motivation and objectives

Global climate change is related with diverse negative environmental and social impacts, such as extinction of species, weather extremes, and resource scarcity that have serious short- and long-term consequences for life on earth (Bundesministerium für Wirtschaft und Klimaschutz, 2022; Intergovernmental Panel on Climate Change, 2021; World Commission on Environment and Development, 1987). A significant part of the climate change can be traced back to the industrial manufacturing of goods and services by worldwide operating companies. The global trade of products and services has lead to significantly raised life expectancy and living standards for many peoples around the world, but has also been accompanied by a massive exploitation of renewable and especially non-renewable natural resources, despite various technical, societal, scientific, and economic innovations (Balderjahn, 2021; Hutter, 2012; Kanning, 2013). Simultaneously, the division of labor, automation, and mass production has led to the emergence of many economic and social questions about the remuneration and working conditions of employees as well as the participation of different social classes on the created wealth. These economic, environmental, and social concerns are related to the business activities of companies, which play a central role for their solution. To meet these global challenges, it requires a corresponding adjustment of the corporate objectives as well as a management approach that pays more attention on the environmental and social consequences of a company's business activities (Dyckhoff and Souren, 2008, p. 45-73; Littig and Grießler, 2004, p. 25-33; Müller-Christ, 2020, p. 121-123).

Companies are special designed entities for the pursuance of the goals of their stakeholders. To these interest groups belong all parties that pursue with their participation in the company their own objectives or are effected by the business activities, such as non-governmental organizations, customers, or suppliers (Freeman et al., 2007; Jensen, 2010). They have different types of goals, such as monetary compensation, self-development, or other non-monetary benefits, that vary in priority and time reference. While some interest groups have common goals and cooperate with one another for their achievements, the objectives of some other groups are incompatible, what leads to short- and long-term stakeholder conflicts. The stakeholders groups are usually subdivided into primary and secondary ones (Freeman et al., 2004). Primary stakeholders consist of all interest groups that benefit from the development of a company and are directly affected by its business activities, such as equity holders, debt holders, employees, customers, and the state. Secondary stakeholders do not have a direct connection with a company and are indirectly affected by its business activities, such as non-governmental organizations, local residents, and the public (Jensen, 2010). However, the distinction between these stakeholder groups is not always clear, and the final assignment of a stakeholder to one of these categories is not possible and depends on the corporate situation and stakeholder issues.

For the achievement of the stakeholder goals, sustainability management aggregates the individual stakeholder objectives to corporate goals. This means in particular that sustainability management categorizes the stakeholder objectives, whereby they are usually subdivided into economic, environmental, and social ones (Lozano, 2008; Weinrich, 2015, p. 8; Wördenweber, 2017, p. 7). These three sustainability goal dimensions need to be weighted according to a company's pursued management approach, because making decisions for instance on investments into production facilities, salary negotiations, or relocation of the production site affects goals from all three sustainability dimensions. Regarding the particular weights of the sustainability dimensions, the literature distinguishes between a classic and an economic triple-bottom-line approach. In the classic triple-bottom-line approach, all three sustainability dimensions are weighted equally, whereas in an economic triple-bottom-line approach the economic dimension dominates the environmental and social ones (Elkington, 1999; Jänicke, 2010, p. 12-22; Müller-Christ, 2020, p. 121-123). However, the classic and economic triple-bottom-line approaches are only two special cases. In corporate practice, the weighting of the corporate goals mostly depends on different company-specific reasons and the respective decision situation. After defining a company's economic, environmental, and social objectives, sustainability management aligns all operating and financing activities of a company in consideration of the impacts along the value added chains on the determined corporate goals (Dierkes et al., 2016, p. 240).

For the achievement of a company's economic, environmental, and social objectives, sustainability management develops different business strategies. The corporate decision-makers choose the business strategy from the strategy portfolio that generates regarding the corporate goals the highest value. After the implementation of the business strategy, the resulting sustainability impacts are reported to the stakeholders and change processes are initiated for a continuous improvement of the company's economic, environmental, and social performance. The main influencing factors on the stakeholder objectives, the subdivision of the stakeholder groups into primary and secondary ones, and the derivation of the corporate goals are illustrated in Figure 1.

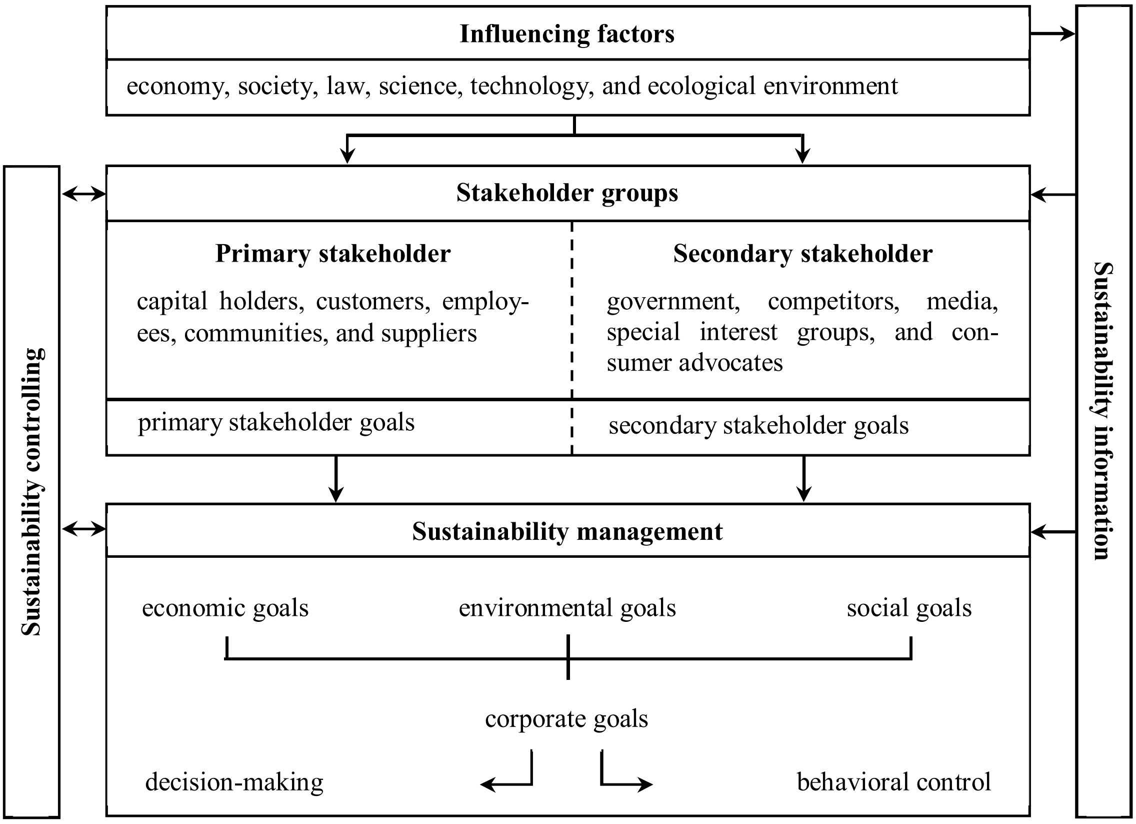

Figure 1: Sustainability management and corporate goals

For the evaluation of a business strategy and its implementation, sustainability management relies on detailed information that it obtains from sustainability controlling. In sustainability controlling, the focus is on the creation of economic, environmental, and social knowledge to provide sustainability management a suitable information base for corporate decision-making and behavioral control (von Ahsen, 2013, p. 175-1867; Weber and Schäffer, 2008, p. 18-28; Weber et al., 2012, p. 68; Zvezdov and Schaltegger, 2012). However, in the past, its primary focus was on the goals of the capital holders. Therefore, the most controlling tools, such as discounted cash flow approaches, cost accounting systems, or incentive systems are focused on the financial success of the equity and debt holders and, thus, contribute solely to the creation of shareholder value (Koller et al., 2020; Ewert and Wagenhofer, 2014, p. 235-289; Kilger et al., 2012). Nevertheless, there exist also some environment- and social-oriented management tools, such as life cycle assessments or social balance sheets. These instruments only generate ecological or social information that is difficult to align with the economic knowledge. But for corporate decision-making and behavioral control, sustainability management requires coordinated economic, environmental, and social information. Thus, for sustainability controlling, there is a need to develop appropriate information instruments, which will create such coordinated information and thus assist sustainability management in the improvement of a company's sustainability performance. Two information tools that belong to this group of suitable controlling instruments are material flow cost accounting and value added statements, which have so far been scarcely considered in sustainability management in corporate practice (Dierkes and Siepelmeyer, 2019, p. 484; Günther et al., 2017, p. 6; Haller et al., 2018).

Material flow cost accounting belongs to the environmental cost accounting systems, which focus on the measurement of the costs of a company's unintended co-products and include cost accounting instruments such as residual material cost accounting, resource cost accounting, or environment-oriented activity-based costing (Fischer, 1998; Jing and Songqing, 2011; Stürznickel et al., 2012). Material flow cost accounting, which is primarily characterized by a separate disclosure of the costs of the products as well as material and product losses, was developed at the end of the 20th century. It investigates the transformation processes of the material and energy flows in quantity centers and separately discloses their corresponding costs (International Organization for Standardization [ISO], 2011, p. 8; May and Günther, 2020, p. 3; Schrack, 2016, p. 159). Moreover, material flow cost accounting includes the four cost categories: material, energy, system, and waste management costs, as well as the use of the material distribution key for cost allocation. In corporate practice, it is applied only in a few case studies for the measurement of a company's actual costs (Byrne and O'Regan, 2016; Dekamin and Barmaki, 2019; Mahmoudi et al., 2017). The limited application of this tool can be traced back to the use of technical terms such as quantity centers, cost categories, or the material distribution key, which are unknown from other environmental cost accounting systems and thus raise fundamental concerns regarding the integration of material flow cost accounting into other established cost accounting systems (Günther, 2008, p. 271-276; Günther et al., 2017; Nakajima, 2004). Moreover, material flow cost accounting lacks of a production theory-based foundation as known from other cost accounting systems, what makes its primary use as an actual cost accounting system comprehensible. For the same reason, the knowledge of the impacts of the different influencing factors, such as waste and rejects, as well as reworking and recycling on the material and product loss creation is unclear, which makes a differentiated analysis of a company's resource efficiency impossible. However, for corporate decision-making and behavioral control in sustainability management, planned cost information is required. To obtain such knowledge, material flow cost accounting has to be designed as a planning cost accounting system, which has not been done in the literature so far. Therefore, the first research question of this thesis is as follows:

"***How to develop a production theory-based material flow cost accounting system for budgeting the costs of the products and the ones of the material and product losses?"***

Value added statements were developed in the 19th century to measure a country's gross domestic product and its distribution among households, companies, and the state (Haller, 1997, p. 77-83; Weber, 1980, p. 8-13; Wenke, 1987). On corporate level, they are used to determine the success of a company from the perspective of multiple stakeholders by determining the created value added and analyzing its distribution among the stakeholders (Aldama and Zicari, 2012, p. 488; Dierkes et al., 2016, p. 243; Haller, 1997, p. 29-47). Due to their stakeholder orientation, value added statements are able to provide comprehensive information on the impacts of a company's business activities on the successes of its different stakeholders. But value added statements are only used for annual reporting on a company's past value added creation and distribution. For corporate decision-making and behavioral control, the management primarily uses discounted cash flow approaches that determine the value of a company from the perspective of the equity and debt holders. The successes of a company's non-financial stakeholders are included in these valuation approaches, but their successes are not separately disclosed in the valuation results. To measure the future successes of a company's stakeholders and determine their present value, it requires a value added-oriented valuation approach. To implement this approach, the focus of in value added statements need to be shifted from the representation of the past to the prediction of the future value added creation and distribution. However, the development of future-oriented value added statements based on a suitable value driver model has not been described in literature yet. Moreover, it is unclear how to determine value of the future successes of a company's stakeholders against the background of a multiperiodic time horizon. Further, it is unknown how such an approach can be integrated into the already existing discounted cash flow approaches, which would increase its theoretical and practical acceptance. It must also be clarified to what extent such a stakeholder-oriented information tool can be applied for sustainability management in corporate decision-making and behavioral control. Accordingly, the second research question of this thesis is:

"How to develop a value added-oriented valuation approach for the determination of the successes of a company's stakeholders?"

According, to the two formulated research questions, this thesis focuses on the further development of material flow cost accounting and value added statements as suitable information tools that provide sustainability management consistent economic-environmental and economic-social information. The findings of this research will help increase the transparency of the material and energy flows inside a company and their related costs, which will consequently improve a company's economic and environmental performance. Moreover, this thesis emphasizes the need for a stronger consideration of stakeholder interests in strategic decision-making. The thesis consists of three studies, whose main contributions and progress in the publication process are illustrated in Figure 2.

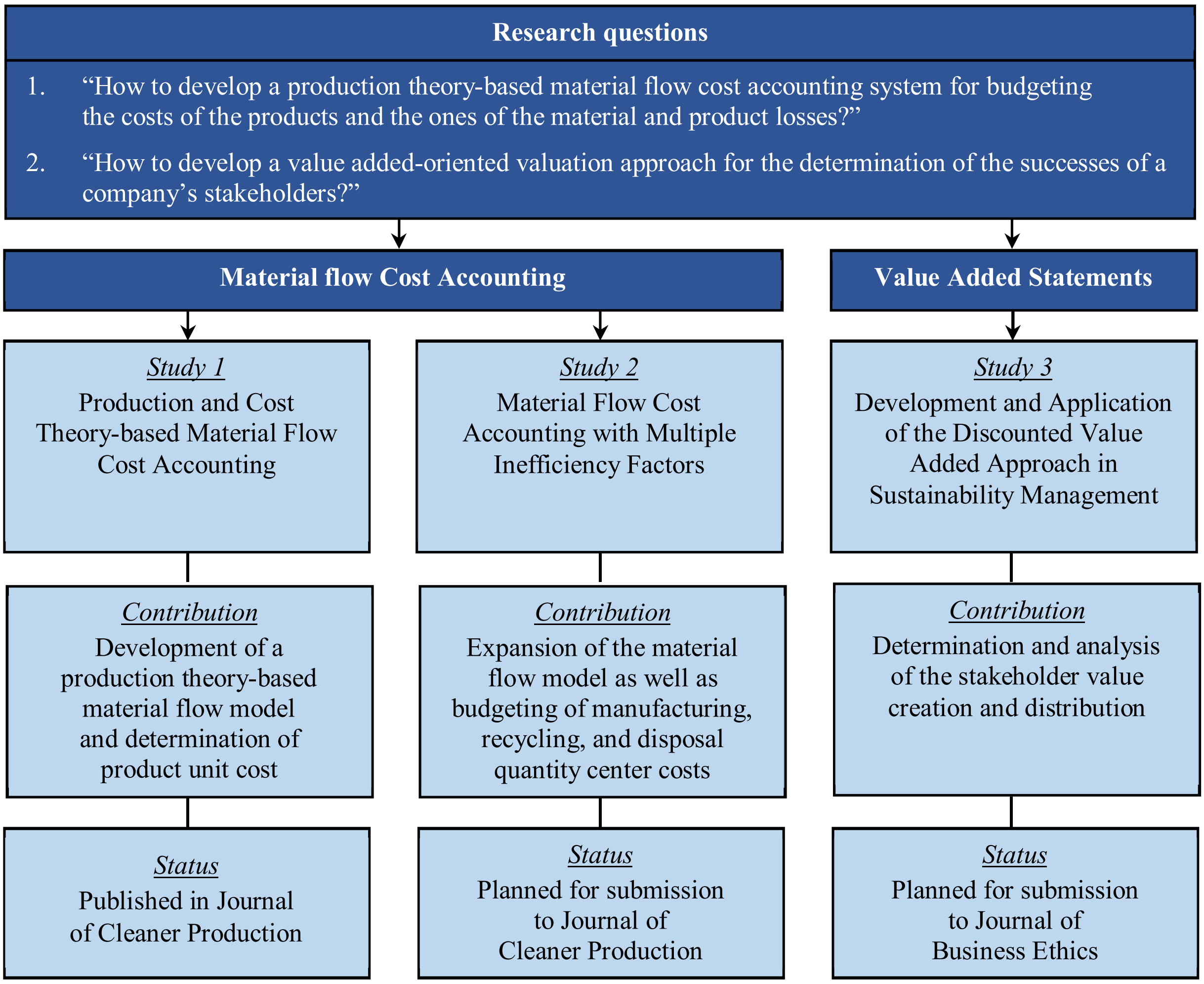

Figure 2: Structure and objectives of the thesis

1.2 Structure and content

The first and second study of this thesis focus on the further development of material flow cost accounting, whereas the third one examines the theoretical expansion of value added statements for their use in sustainability management. The first study develops a production-theoretical foundation for material flow cost accounting. In this study, the material demand is determined in consideration of waste and rejects as well as the budgeting of the efficient and inefficient quantity center costs are described (Chapter 2). The second study develops a material flow model considering the influencing factors waste, reject, reworking, and recycling. Moreover, it demonstrates the budgeting of the manufacturing, recycling, and disposal quantity center costs and determines the product unit costs (Chapter 3). In the third study, future-oriented value added statements are developed based on already existing internal forecast calculations that are used to determine the future created and to the workers, community, equity holders and debt holders distributed stakeholder value. Moreover, different analysis dimensions are used for a single- and multi-dimensional analyses of the determined market values, which are also used for the development of value added- and stakeholder-related key ratios (Chapter 4). The thesis concludes with a summary of the main findings and a discussion of the three studies' major limitations (Chapter 5).

Study 1: Production and Cost Theory-based Material Flow Cost Accounting (Chapter 2)

Inefficiency factors are responsible for the emergence of unintended material and product losses in corporate production processes, which lead to serious financial and environmental burdens. In this context, material flow cost accounting is one of the most promising environmental cost accounting tools for the reduction of these unintended co-products and, thus the improvement of a company's resource efficiency. But in corporate practice, its application is severely limited to few manufacturing companies due to its theoretical shortcomings and the missing description of its connections to other existing cost accounting systems. Therefore, the first part of this study begins with the development of a production and cost theory-based material flow model for a manufacturing company considering the effects of waste and rejects on the material demand in complex production processes. Afterwards, the determined demand for raw materials and products is subdivided into efficient and inefficient material demand. Moreover, the level and composition of the material demand are analyzed at the company, quantity center, and product unit levels. The second part starts with a discussion of the major assumptions of the material flow cost accounting system and a description of the main budgeting steps for efficient and inefficient production costs. Subsequently, the quantity center costs are allocated to the single product units to determine the product unit costs. Finally, for the provision of short-term environmental cost information, the conception and application of material flow cost accounting as a marginal cost accounting system are briefly discussed.

Study 2: Material Flow Cost Accounting with Multiple Inefficiency Factors (Chapter 3)

Due to legal requirements and the increasing shortage of major raw materials, environmental protection measures, such as reworking and recycling, have become important for the improvement of a company's resource efficiency. For this reason, this study starts with a detailed description of the creation and reduction of the material and product losses in multi-stage corporate transformation processes as well as the identification of the manufacturing, recycling, and disposal quantity centers. The development of a production theory-based material flow model enables the determination of a company's material demand in consideration of the effects of waste, rejects, reworking, and recycling. Product- and material-oriented input-output tables have been created to analyze the material flows at the quantity center level, which quantities are then allocated to the product unit level. In the second part of this study, the structure and application of a material flow cost accounting system for the budgeting of the manufacturing, recycling, and disposal quantity center costs are described. The quantity center costs are allocated from the three quantity center types to the single product units based on suitable cost allocation rates. Afterwards, the product unit costs are determined and the cost increasing and decreasing impacts of waste, rejects, reworking, and recycling are analyzed at product unit level using appropriate cost calculation schemes. Finally, the consequences for material flow cost accounting that results from the use of the material distribution key are discussed and possible alternatives for cost allocation are shown.

Study 3: Development and Application of the Discounted Value Added Approach in Sustainability Management (Chapter 4)

In value-oriented management, discounted cash flow approaches are primarily used to determine the created shareholder value. However, the influence of customers, employees, and the state on corporate management has increased in the last few decades and has made a stronger consideration of their objectives in corporate decision-making inevitable. For this purpose, value added statements possess, due to their stakeholder-oriented definition of the corporate success, a great potential use for the provision of stakeholder-related knowledge. However, currently, this information tool is primarily used in corporate practice for sustainability reporting. To enable the theoretical and practical integration of this tool into sustainability management, the third study develops the discounted value added approach. This study starts with the development of future-oriented value added statements on cash flows and the forecast of the future value added creation and distribution for an infinite time horizon. Afterwards, the discounted value added approach is developed by combining the planned value added statements with a discounted cash flow approach. The new valuation approach discounts the future value added with appropriate costs of capital for the calculation of the stakeholder value. The determined market value is subdivided among the workers, community, debt holders, and equity holders. The second part of this study examines the stakeholder value and the market values of the successes of these four interest groups regarding different economic and social analysis dimensions for the additional creation of value added- and stakeholder-related knowledge. Additionally, the analysis of the stakeholder value creation and distribution reveals some environmental impacts that are related to a company's business activities. Finally, it is demonstrated how the discounted value added approach is used for the identification of suitable value added- and stakeholder-related key ratios that can assist sustainability management in short- and long-term corporate decision-making and behavioral control.

2. Production and Cost Theory-Based Material Flow Cost Accounting

Stefan Dierkes and David Siepelmeyer

Abstract

We develop a material flow cost accounting system for planning efficient and inefficient costs in arbitrary production processes. The basis of this accounting system is a material flow model with waste and rejects as the main factors of material losses, which is used to determine efficient and inefficient material demand at quantity center and product unit level. This production theoretical foundation enables an extension of the known material flow cost accounting system by a cost unit accounting and clarifies the relationships to other cost accounting systems. Finally, we discuss the necessary steps to implement material cost accounting as a marginal cost accounting system to provide relevant information for short-term decisions.

Keywords

Material flow cost accounting, Environmental cost accounting, ISO 14051, Sustainability management

JEL-Classification

Q56

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2.1 Introduction

In the last few years, companies have increasingly turned toward sustainable management. This trend is characterized by extending business activities from primarily economic goals to also encompass ecological and social goals (Baumast and Pape, 2022; Dyllick and Hockerts, 2002; Elkington, 1999). Regardless of the weighting of the three sustainability dimensions, the relevance of information about the ecological impacts of a company's business activities on its surroundings has increased. Due to changes in the public's interest in the environment and the influence of waste and rejects on natural capital, management has a need for additional information. These information needs cannot be satisfied using widespread cost accounting systems, such as marginal costing or activity-based costing, which are primarily focused on economic goals. Therefore, development of material flow cost accounting (MFCA) is logical, because this management instrument improves transparency of material flows and energy consumption in companies. It also provides information for making decisions that consider environmental impacts. Moreover, the use of MFCA leads to improvement in the coordination and communication of material and energy usage in organizations (Christ and Burritt, 2015; Günther et al., 2016; Schmidt and Nakajima, 2013).

MFCA is a version of environmental cost accounting that especially considers input, process, and product-related costs of environmental effects. The development of environmental cost accounting systems such as ecology-oriented cost accounting and process-oriented environmental cost accounting originated in German-speaking regions mainly in the 1990s (Frese and Kloock, 1989; Keilus, 1993; Letmathe, 1998; Roth, 1992). In other regions, increasing environmental concerns have also led to interest in companies' environmental impacts, which resulted in discussions regarding the general requirements of environmental cost accounting systems and their relationship with other cost accounting systems (Burritt et al., 2008; Epstein, 1996; Jasch, 2003; Letmathe and Doost, 2000). The publication in 2011 of the international standard for MFCA (ISO 14051) brought new attention to environmental cost accounting systems (Kokubu and Nashioka, 2005; Loew et al., 2003; Nakajima, 2004; Schmidt and Nakajima, 2013). The progressive development of MFCA and increasing scarcity of non-renewable resources as well as the massive environmental impacts of material losses from industrial production led to the application of MFCA in industries like wood products and furniture producers, the oil producing sector, soybean production, and metal producers. In these industries, MFCA is introduced to measure the current costs of material and energy flows and reduce undesired material losses

(Chompu-inwai et al., 2015; Dekamin and Barmaki, 2019; Dunuwila et al., 2018; Mahmoudi et al., 2017; Schmidt and Nakajima, 2013; Sygulla et al., 2014). In addition to the implementation of this instrument in some industries, new demands have occurred for expanding MFCA to supply chains because of the potential material loss savings when there is closer cooperation between suppliers and buyers (Nakajima et al., 2015; Prox, 2015; Schrack, 2016). This proposal would enable reducing not only a single company's material losses, but also the avoidance of a significant proportion of all material losses that occur in the transformation processes along a supply chain. Furthermore, MFCA seems suitable for consideration of long-term goals like resource efficiency in management control systems (Rieckhof et al., 2015). Besides MFCA, some related environmental management instruments such as embodied water accounting and thermo-ecological costing have evolved that measure the quantities of particular resources as inputs or outputs of production processes (Byrne and O'Regan, 2016; Passarini et al., 2014; Shao and Chen, 2016; Stanek et al., 2015; Tiskatine et al., 2018). Other environmental management tools such as ecological footprint accounting explicitly consider the externalized effects of production processes by monetizing their influence on the company's surroundings (Bagliani and Martini, 2012; Mikulčić et al., 2016; Schmidt, 2015).

However, one reason for the limited implementation of MFCA in just a few industries lies in its significant differences from other widespread cost accounting systems. MFCA uses several unusual definitions compared to conventional cost accounting systems, such as quantity centers instead of cost centers and cost categories instead of cost types. Moreover, it includes some elements that do not exist at all in other cost accounting systems, such as a material flow cost matrix, while certain core elements of common cost accounting systems, such as unit cost accounting, are missing or are at least scarcely mentioned (Christ and Burritt, 2015; Günther et al., 2015; Jasch, 2009; Schmidt, 2011; Schrack, 2016). Another reason for the limited usage of MFCA in practice is its explanation in the literature using examples with simple performance relationships among quantity centers whereas production processes in practice are significantly more complex.

Furthermore, until now MFCA has especially been used in practice to analyze current costs and not as a planning tool; this can be traced back to its lack of a production and cost-theory foundation. Consequently, the process of budgeting material and energy flow costs in MFCA remains unclear. However, information on future material and energy flows to determine efficient and inefficient production costs and the ecological guidance of the employees to achieve resource efficiency is especially important for management. In addition, the impacts on material losses of different inefficiency factors like waste and rejects have not been analyzed in detail. Only a deep understanding of the reasons behind such inefficiencies allows the identification of potential solutions for a focused reduction of material losses in quantity centers. Moreover, until now, there has been no detailed discussion of the process of budgeting the different cost categories or their relationships to common cost types (ISO, 2011; Sygulla et al., 2011). The focus in MFCA is mainly on the material and energy flow transformation processes in quantity centers. However, for management are the costs of material losses and the influence of the inefficiency factors on product unit costs important, but this information is currently not provided by MFCA. To create short-term information at the product unit level, costs in MFCA need to be analyzed regarding their behavior in response to changes in production volumes, but because MFCA is usually designed as a full cost accounting system, it does not distinguish between variable and fixed costs (Schmidt et al., 2015).

To overcome these shortcomings, we present in this paper a production and cost theoretical foundation for MFCA by the development of a differentiated material flow model, as it is known in other cost accounting systems, for budgeting production costs (Kilger et al., 2012; Kloock, 1969; Kloock and Schiller, 1997; Schmidt, 2005). Based on this material flow model, efficient and inefficient material demand can be budgeted depending on the company's sales volume and changes in inventories, which can also be useful for related environmental accounting systems like virtual water or life cycle assessment (Bagliani and Martini, 2012). Moreover, the production theoretical foundation offers the opportunity to analyze the material and energy flows in detail on quantity center and product unit level in complex production processes, as well as determine their dependence on the inefficiency factors waste and rejects (Keilus, 1993; Kilger et al., 2012; Krüger, 1959). In addition, we clarify the process of budgeting costs in MFCA on a full cost accounting system. For this purpose, we analyze the determination of the cost types in quantity centers and their aggregation to cost categories as well as the development of a sound material flow cost matrix and cost unit accounting. Finally, describing the opportunity to subdivide efficient and inefficient costs into their variable and fixed components in MFCA, we enable the determination of short-term decision-useful information for management in a marginal cost accounting system.

This paper is structured as follows. In the second section, we develop a production and cost-theory based material flow model that allows the determination and analysis of efficient and inefficient material and energy flows at the quantity center and product level considering the inefficiency factors of waste and rejects. In the third section, we describe the conception of MFCA as a full cost accounting system, including the calculation of efficient and inefficient costs at the quantity center and product level as well as the aggregation of the cost types to cost categories and the use of the material flow cost matrix. We also discuss the opportunity to subdivide efficient and inefficient costs into their variable and fixed components. The paper concludes with a summary of the paper's scientific and practical contributions and a description of potential directions for future research in the field of MFCA.

2.2 Production theory-based material flow model

2.2.1 Determination of efficient and inefficient material demand

For budgeting production costs in arbitrary production processes with MFCA, we need a material flow model that allows the determination of efficient and inefficient material demand. In our material flow model, we divide the production area into J quantity centers with j as a quantity center index $j = 1,\dots,J$. A quantity center is a selected part of a company or a process for which input and output are measured in physical and monetary units (ISO, 2011). Each quantity center produces a product with up to M materials, with m as the material index $m = 1,\dots,M$. The production coefficients $a'_{m,M+j}$ and $a'_{M+k,M+j}$ represent the amount of material m and intermediate product $M+k$, where k is another quantity center index that is used for the production of one product from quantity center j without any inefficiencies. Depending on the sales volume of product xa_{M+j} and changes in inventories Δl_m and Δl_{M+k}, the requirement of materials and products r'_m and r'_{M+j} without inefficiencies are calculated as follows (Boons, 1998; Dörner, 1984; Fandel et al., 2009; Keilus, 1993; Kloock and Schiller, 1997; Schweitzer et al., 2016):

$$\begin{aligned} r'_m = {} & a'_{m,1} \cdot r'_1 + \dots + a'_{m,M} \cdot r'_M \\ & + a'_{m,M+1} \cdot r'_{M+1} + \dots + a'_{m,M+J} \cdot r'_{M+J} + xa_m + \Delta l_m \end{aligned} \qquad \text{with } m = 1,\dots,M \qquad (1)$$

$$r'_{M+j} = a'_{M+j,1} \cdot r'_1 + \ldots + a'_{M+j,M} \cdot r'_M + a'_{M+j,M+1} \cdot r'_{M+1} + \ldots + a'_{M+j,M+J} \cdot r'_{M+J} + xa_{M+j} + \Delta l_{M+j} \quad \text{with } j = 1, \ldots, J \tag{2}$$

Note that the production coefficients $a'_{m,M}$ and $a'_{M+j,M}$ in (1) and (2) are zero, but to obtain a symmetrical equation system, we incorporate these variables as well as the variable xa_m into the equation system. This allows us to determine the total internal demand for materials and products by transforming equations (1) and (2) to matrixes, where $\underline{r}'$ denotes the vector of the required quantity of materials and products, $\underline{A}'$ represents the matrix of production coefficients, $\underline{xa}$ stands for the vector of product sales volumes, and $\underline{\Delta l}$ denotes the vector of changes in inventories:

$$\underline{r}' = \underline{A}' \cdot \underline{r}' + \underline{xa} + \underline{\Delta l} \tag{3}$$

After solving (3) for vector $\underline{r}'$ using the identity matrix $\underline{E}$, we obtain the matrix of the total internal demand coefficients $\underline{B}'$.

$$\underline{r}' = (\underline{E} - \underline{A}')^{-1} \cdot (\underline{xa} + \underline{\Delta l}) = \underline{B}' \cdot (\underline{xa} + \underline{\Delta l}) \tag{4}$$

Therefore, total internal demand for materials and products without any inefficiencies in quantity centers can be determined using (4). To consider waste and rejects as the main sources of inefficiencies, the net quantity of materials and products must be adjusted. Waste as an input-related inefficiency is represented by the production coefficients $\alpha_{m,M+j}$ and $\alpha_{M+k,M+j}$ (Keilus, 1993; Kilger et al., 2012). These coefficients represent the amount of waste of material m or intermediate product $M+k$ for the production of a product unit $M+j$. The waste-related production coefficient can be calculated as the sum of all factors that lead to waste, such as material quality, intensity of the production process or cutting losses. Consequently, the waste-related production coefficients $\alpha_{m,M+j}$ and $\alpha_{M+k,M+j}$ represent the standardized amount of waste that usually arises in a production process. If we increase the coefficients $a'_{m,M+j}$ and $a'_{M+k,M+j}$ by the waste-related production coefficients, we obtain the adjusted coefficients $a_{m,M+j}$ and $a_{M+k,M+j}$. In contrast to waste, rejects are an output-related inefficiency factor (Kilger et al., 2012). The reject rate β_{M+j} represents the percentage of the output from quantity center $M+j$ that does not meet the pre-assigned quality standard and is treated as a material loss. Therefore, the production yield and rejects of a quantity center can be calculated as $(1-\beta_{M+j})\cdot r_{M+j}$ and $\beta_{M+j}\cdot r_{M+j}$. After considering waste-related production coefficients and reject rates, the equation system can be rearranged to determine the total internal demand of r_m and r_{M+j}, including inefficiencies:

$$\begin{aligned} r_m = {} & a_{m,1}\cdot r_1 + \ldots + a_{m,M}\cdot r_M \\ & + a_{m,M+1}\cdot r_{M+1} + \ldots + a_{m,M+J}\cdot r_{M+J} + xa_m + \Delta l_m + \beta_m \cdot r_m \end{aligned} \qquad \text{with } m = 1,\ldots,M \qquad (5)$$

$$\begin{aligned} r_{M+j} = {} & a_{M+j,1}\cdot r_1 + \ldots + a_{M+j,M}\cdot r_M \\ & + a_{M+j,M+1}\cdot r_{M+1} + \ldots + a_{M+j,M+J}\cdot r_{M+J} + xa_{M+j} + \Delta l_{M+j} + \beta_{M+j} \cdot r_{M+j} \end{aligned} \qquad \text{with } j = 1,\ldots,J \qquad (6)$$

This equation system can also be transformed to matrixes, where $\underline{A}$ represents the matrix of the adjusted production coefficients and $\underline{W}$ denotes the matrix of the reject rates. The vector for the gross quantity of materials and products considering waste and rejects $\underline{r}$ and the matrix of the adjusted total internal demand coefficients $\underline{B}$ can be calculated with (7):

$$\underline{r} = (\underline{E} - (\underline{A} + \underline{W}))^{-1} \cdot (\underline{xa} + \underline{\Delta l}) = \underline{B} \cdot (\underline{xa} + \underline{\Delta l}) \qquad (7)$$

For a production process with two materials and two products, the basic idea of this material flow model, including the relationships between materials, products, sales, changes in inventory, and rejects, is illustrated in Figure 3.

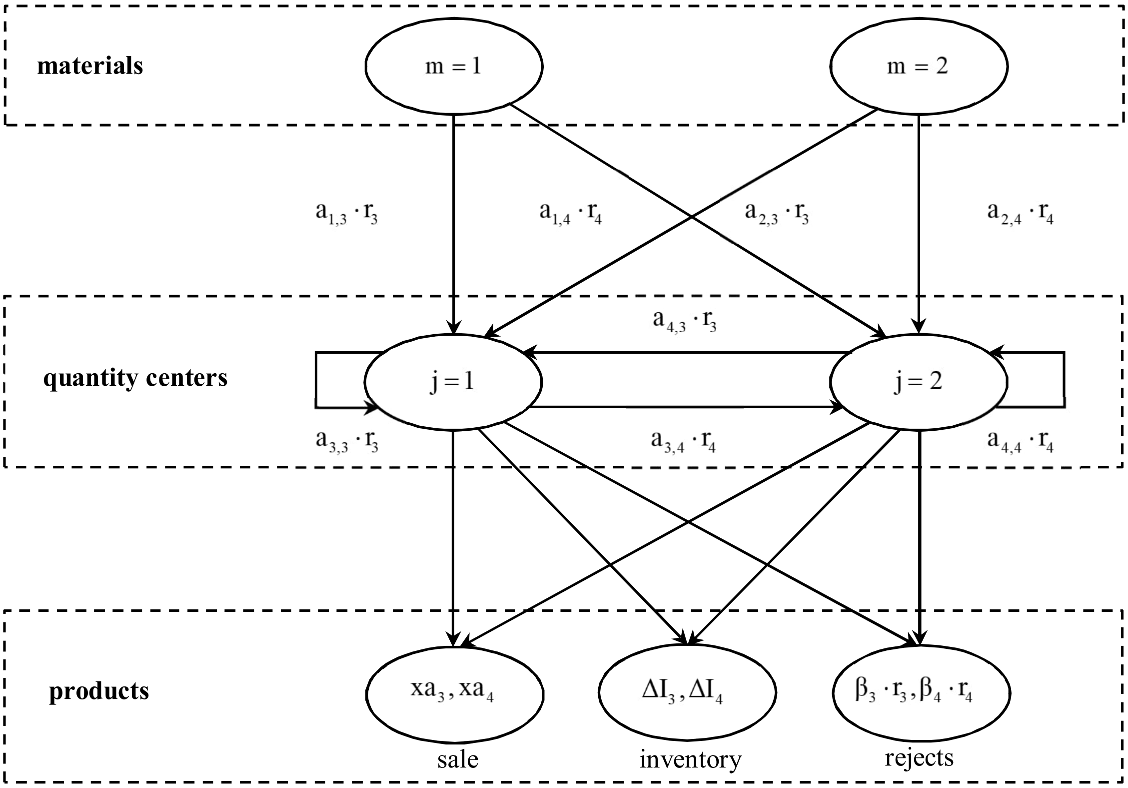

Figure 3: Material flow model with two materials, quantity centers, and products

The vector of the waste- and reject-related material loss $\underline{v}$ can be determined by subtracting vector $\underline{r}'$ from vector $\underline{r}$:

$$\underline{v} = \underline{r} - \underline{r}' = (\underline{B} - \underline{B}') \cdot (\underline{xa} + \underline{\Delta l}) \tag{8}$$

Therefore, the losses of material m in any production process can be calculated using the total internal demand coefficients with and without inefficiencies $b_{m,M+j}$ and $b'_{m,M+j}$:

$$v_m = \sum_{j=1}^{J} (b_{m,M+j} - b'_{m,M+j}) \cdot (xa_{M+j} + \Delta l_{M+j}) \tag{9}$$

Furthermore, (9) also enables the decomposition of the waste- and reject-related material losses and their allocation to products using methods of deviation analysis. Additionally, we can consider efficient and inefficient demand for raw materials and products that is independent of the production quantity. An important question regarding the variable material demand is how much of the material losses can be traced back to the inefficiencies in a single quantity center. Therefore, determination of material demands in quantity centers is analyzed in detail in section 2.2.2.

2.2.2 Determination of material demand in quantity centers

The demand for materials at a quantity center consists of a primary and a secondary material demand (Kloock and Schiller, 1997). Primary material demand as the demand for materials is calculated using the product of the coefficient $a_{m,M+j}$ and the gross quantity of product r_{M+j} from quantity center $M+j$. However, secondary material demand is determined based on the intermediate products that quantity center $M+j$ receives from other quantity centers. The amount of intermediate products $r_{M+k,M+j}$ delivered from quantity center $M+k$ to $M+j$ is determined as follows:

$$r_{M+k,M+j} = (a'_{M+k,M+j} + \alpha_{M+k,M+j}) \cdot r_{M+j} \tag{10}$$

In MFCA, only efficient material demand is attributed to intermediate products. Inefficient material demand, which can be traced back to waste and rejects, is not allocated to products but remains in the quantity centers and is disclosed as material loss (ISO, 2011). Therefore, the secondary material demand of material m in quantity center $M+j$ is calculated as the product of the total internal demand coefficient without inefficiencies $b'_{m,M+k}$ and the amount of intermediate product $r_{M+k,M+j}$ that quantity center $M+j$ receives from quantity center $M+k$. Accordingly, we obtain the sum of the primary and secondary material demand $r^*_{m,M+j}$ of quantity center $M+j$:

$$
\begin{aligned}
r^{*}_{m,M+j} &= (a'_{m,M+j} + \alpha_{m,M+j}) \cdot r_{M+j} + \sum_{k=1}^{J} b'_{m,M+k} \cdot (a'_{M+k,M+j} + \alpha_{M+k,M+j}) \cdot r_{M+j} \\
&= \underbrace{a_{m,M+j} \cdot r_{M+j}}_{\substack{\text{primary} \\ \text{material demand}}} + \underbrace{\sum_{k=1}^{J} b'_{m,M+k} \cdot a_{M+k,M+j} \cdot r_{M+j}}_{\substack{\text{secondary} \\ \text{material demand}}}
\end{aligned} \tag{11}
$$

If we disregard the effects of the inefficiency factors of waste and rejects on the material demand in (11), we obtain the efficient material demand $re_{m,M+j}$:

$$
re_{m,M+j} = \underbrace{a'_{m,M+j} \cdot (1-\beta_{M+j}) \cdot r_{M+j}}_{\substack{\text{efficient primary} \\ \text{material demand}}} + \underbrace{\sum_{k=1}^{J} b'_{m,M+k} \cdot a'_{M+k,M+j} \cdot (1-\beta_{M+j}) \cdot r_{M+j}}_{\substack{\text{efficient secondary} \\ \text{material demand}}} \tag{12}
$$

The difference between material demand $r^{*}_{m,M+j}$ and efficient material demand $re_{m,M+j}$ is the inefficient material demand $v_{m,M+j}$ of material type m in quantity center $M+j$, which is caused only by inefficiencies in this quantity center. Additionally, using (11) and (12) to determine inefficient material demand, the material loss of material m can be divided into primary and secondary inefficient material demand and further into primary and secondary waste- and reject-related material loss:

$$
\begin{aligned}
v_{m,M+j} &= r^{*}_{m,M+j} - re_{m,M+j} \\
&= \underbrace{\alpha_{m,M+j} \cdot (1-\beta_{M+j}) \cdot r_{M+j}}_{\substack{\text{primary waste-related} \\ \text{material loss}}} + \underbrace{a_{m,M+j} \cdot \beta_{M+j} \cdot r_{M+j}}_{\substack{\text{primary reject-related} \\ \text{material loss}}} \\
&\quad + \underbrace{\sum_{k=1}^{J} b'_{m,M+k} \cdot \alpha_{M+k,M+j} \cdot (1-\beta_{M+j}) \cdot r_{M+j}}_{\substack{\text{secondary waste-related} \\ \text{material loss}}} + \underbrace{\sum_{k=1}^{J} b'_{m,M+k} \cdot a_{M+k,M+j} \cdot \beta_{M+j} \cdot r_{M+j}}_{\substack{\text{secondary reject-related} \\ \text{material loss}}}
\end{aligned} \tag{13}
$$

Adding up the material losses from all quantity centers, we obtain the company's total material loss of material m, which we already know from (9):

$$v_m = \sum_{j=1}^{J} v_{m,M+j} \tag{14}$$

The relationship between primary and secondary material demand as well as efficient and inefficient material demand in a quantity center is illustrated in Figure 4.

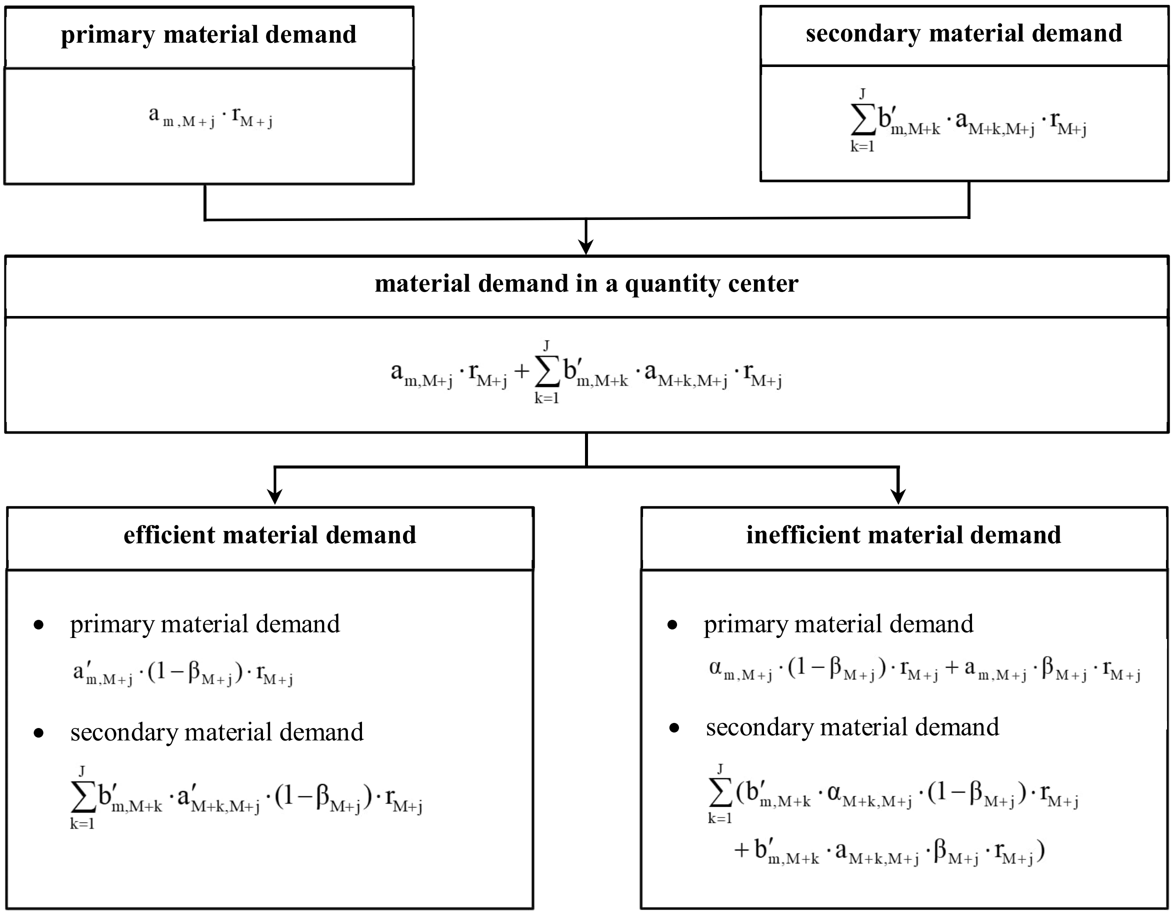

Figure 4: Primary, secondary, efficient, and inefficient material demand in a quantity center

Finally, we have now determined the efficient and inefficient material demand of all quantity centers. The remaining question is how to attribute efficient and, in particular, inefficient material demand to product units.

2.2.3 Determination of material demand per product unit

In our material flow model, we have previously determined the efficient demand coefficient

$b'_{m,M+j}$. This coefficient can also be calculated by dividing the efficient material demand at a quantity center using (12) by the production yield $(1-\beta_{M+j})\cdot r_{M+j}$.

$$b'_{m,M+j} = \frac{re_{m,M+j}}{(1-\beta_{M+j})\cdot r_{M+j}} \tag{15}$$

To ensure transparency of the inefficient material demand, we separately disclose the material losses at the quantity center level. Nevertheless, in the end, the waste- and reject-related material demand depends on the company's sales volume and changes in inventories, which can be seen by the determination of the gross quantity of materials and products using the waste-related production coefficient and reject rates in section 2.2.1. Therefore, we assign the inefficient material demand to product units, which we have already done through the calculation of the total internal demand coefficient $b_{m,M+j}$ (for the corresponding treatment of waste and rejects in a marginal costing system, see Kilger et al., 2012). However, it is useful to separate inefficient material demand from efficient material demand at the product unit level. The inefficient material demand for a product can be determined by subtracting the total internal demand coefficient without inefficiencies from the total internal demand coefficient with inefficiencies:

$$c_{m,M+j} = b_{m,M+j} - b'_{m,M+j} \tag{16}$$

The inefficient material demand $c_{m,M+j}$ is the sum of the material losses in all quantity centers that can be traced back to the production of product $M+j$. However, it is still unknown to what extent the material losses are caused by inefficiency factors in a quantity center. To determine this, we use the amount of material losses from the inefficiency factors $v_{m,M+j}$ in (13). If we use the output of a quantity center to assign material losses to product units, we obtain the allocation rate $ar_{m,M+j}$:

$$ar_{m,M+j} = \frac{v_{m,M+j}}{r_{M+j}} \tag{17}$$

Using the quantity centers' allocation rates and the total internal demand coefficients $b_{M+k,M+j}$, we obtain the inefficient material demand per product unit $c_{m,M+j}$:

$$c_{m,M+j} = \sum_{k=1}^{J} ar_{m,M+k} \cdot b_{M+k,M+j} \tag{18}$$

By (18), we see to what extent the inefficiencies of a specific quantity center affect the material losses of a product unit. To provide additional information about the effects of specific inefficiency factors at a quantity center, we can disaggregate the allocation rates by inserting (13) into (17) to get specific allocation rates for the primary and secondary waste- and reject-related material losses, which might be useful information for environmental and economic decision-making at the product level.

2.3 Conception and application of a material flow cost accounting system

2.3.1 Material flow cost accounting as a full cost accounting system

In the material flow model, we have determined the efficient and inefficient material demand by quantity center and product unit level depending on sales volume and inventory changes. Based on this material flow model, we design a MFCA system, which can be used as an instrument for budgeting costs (Ewert and Wagenhofer, 2014; Friedl et al., 2005). Because it is not common in MFCA to separate costs into variable and fixed costs, we start with MFCA as a full cost accounting system (Günther, 2008; ISO, 2011).

An important element of MFCA is the use of quantity centers as company subdivisions for which inputs and outputs are measured in physical and monetary units. Therefore, in the material flow model, we still subdivided the production area into quantity centers, although companies are usually structured in cost centers (ISO, 2011; Schrack, 2016). To easily integrate

MFCA into other cost accounting systems, we assume that quantity centers are built on the existing cost center structure. Because cost centers are designed especially to consider aspects of responsibility, they usually contain more than one quantity center. Accordingly, cost planning in MFCA should be done at the quantity center level, so exact information is obtained about the costs of the products and material losses in every quantity center. We recommend planning costs at the cost center level only if budgeting costs in a quantity center is not possible or is economically unacceptable. In this case, costs should then be allocated to quantity centers using appropriate allocation rates.

Furthermore, MFCA is characterized by a strict separation of efficient product costs and the inefficient material loss costs at the quantity center and product level to achieve a high level of transparency in material and energy flows. Efficient costs occur in production processes under ideal-typical production conditions and are directly related to the intended output of a quantity center. Inefficiencies in a production process, such as waste and rejects, lead to material losses, which are assigned to the cost of their production (ISO, 2011). We can determine the efficient material and energy costs at the quantity center level based on (12). In the same way, we can use (13) to calculate the inefficient waste- and rejects-related material and energy costs. However, MFCA surprisingly does not have a unit cost calculation that allocates efficient and inefficient costs from the quantity centers to product units, even though this cost information is important for management. Therefore, we expand MFCA using a differentiated cost unit accounting, which will be described in detail later.

Another central element of MFCA is the separation of the costs into the cost categories of material costs, energy costs, system costs, and waste management costs (Günther et al., 2016; ISO, 2011; Schrack, 2016). Material costs, as well as energy costs, are attributed to the cost categories of material and energy costs, which is in line with the material flow model in equations (12) and (13). The category of waste management costs occurs at quantity centers for the treatment and logistics of material losses (ISO, 2011). Therefore, we attribute the inefficient costs resulting from the handling and transportation of material losses to the waste management cost category. In contrast to waste management costs, system costs occur in MFCA for the transformation of inputs to outputs at a quantity center (ISO, 2011). Consequently, the remaining efficient and inefficient costs are assigned to system costs. However, the use of these cost categories in MFCA does not mean that costs are no longer subdivided into cost types like labor costs, material costs, depreciation, and other costs. Using these cost types, we can perform cost planning using known production and cost analysis techniques just as in other cost accounting systems (Bhimani et al., 2015; Ewert and Wagenhofer, 2014; Kilger et al., 2012; Sharman, 2003). The cost types at a quantity center are planned based on the cost drivers sales volume and changes in inventories from (5) and (6) as well as the amount of waste and rejects. Afterwards, the planned costs for each cost type can be split into the four cost categories depending on their occurrence and use in a quantity center's production process.

To consider the performance relationships between different quantity centers, MFCA includes a specific type of secondary cost allocation with the material flow cost matrix. In the literature on MFCA, the relationship between the material flow cost matrix and conventional secondary cost accounting is barely discussed, although they have similarities, but also significant differences (ISO, 2011). In contrast to common secondary cost accounting, the material flow cost matrix allocates only the efficient costs of the delivered intermediate products between quantity centers, whereas the inefficient costs remain in the delivering quantity centers. Furthermore, the material flow cost matrix so far has been used only for simple performance relationships between quantity centers. However, in practice, we find also complex production processes, which should be taken into account in the material flow cost matrix.

All in all, we obtain the structure of MFCA as a full cost accounting system with cost type accounting, quantity center accounting, and cost unit accounting, as illustrated in Figure 5. Therefore, the structure of MFCA corresponds to the structure of other cost accounting systems and can be easily integrated into companies' existing cost accounting systems.

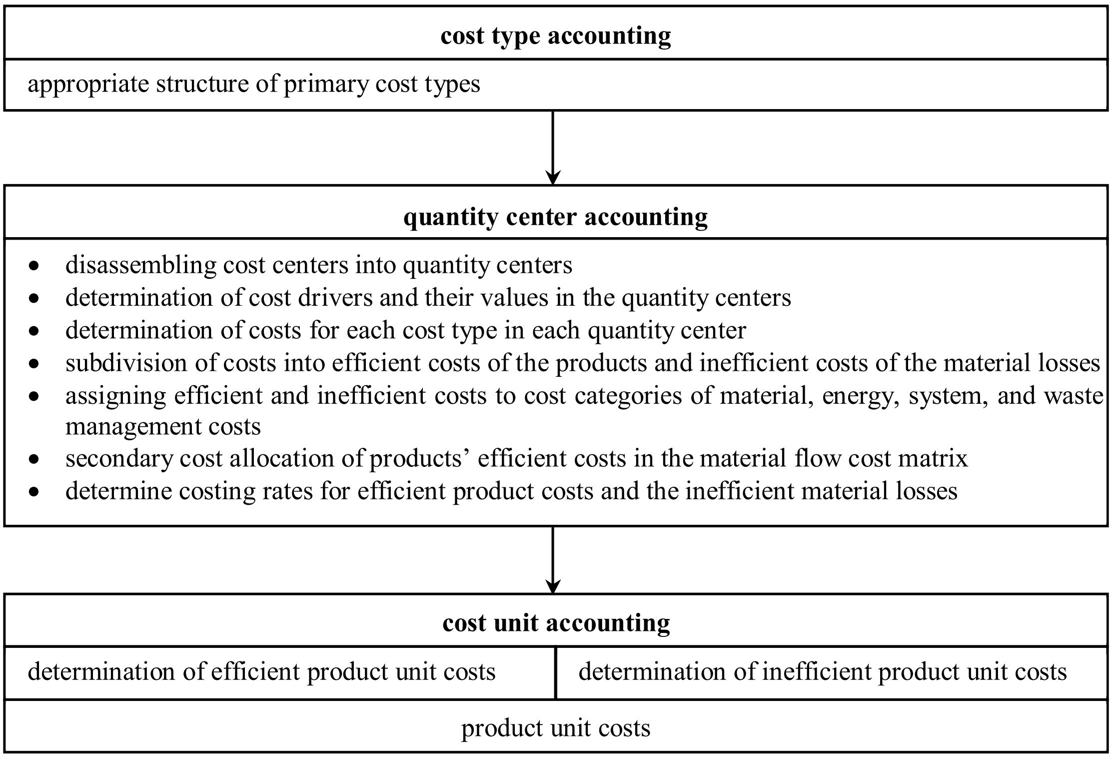

Figure 5: Structure of material flow cost accounting as a full cost accounting system

In this MFCA structure, we separate costs using the three dimensions of cost types, cost efficiency, and cost categories, which is shown in Figure 6. The costs are planned for each cost type at a quantity center and are disaggregated into efficient and inefficient costs afterwards. Finally, efficient and inefficient costs are assigned to cost categories. The disaggregation of costs into these three dimensions at every point in MFCA provides deep insights into the structure and composition of costs, which is indispensable for many tasks in sustainability management (ISO, 2011).

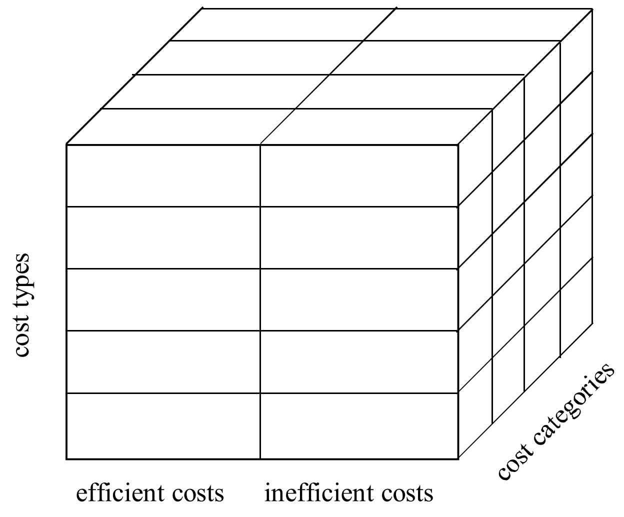

Figure 6: Cost types, cost efficiency, and cost categories as cost dimensions

For secondary cost accounting in MFCA, the material flow cost matrix separately discloses the efficient costs of products and inefficient costs of the material losses (ISO, 2011). Using the material flow model from section 2.2, we can allocate the efficient costs of the intermediate products that are delivered to the receiving quantity centers in complex production processes. Moreover, for a better understanding of the performance relationships among quantity centers, the material flow cost matrix in Table 1 separates efficient and inefficient costs by cost categories, as well as primary and secondary costs.

cost categories		material costs	energy costs	system costs	waste management costs	flow costs
efficient costs of products						
	primary costs					
+	secondary costs					
=	total costs					
–	delivered intermediate products					
=	final costs					
inefficient costs of material losses						
	primary costs					
+	secondary costs					
=	total costs					

Table 1: Differentiated material flow cost matrix of a quantity center

The efficient costs of raw materials at a quantity center are differentiated into the cost categories of material costs, energy costs, and system costs, and are disclosed as primary costs. If a quantity center receives intermediate products from other quantity centers, it is charged with secondary costs, which are also differentiated into the three cost categories. Adding these costs results in the efficient total costs for a quantity center. When we add the different cost categories, we obtain the efficient flow costs (Günther, 2008). Furthermore, a quantity center is cleared by the efficient costs of its products, which are delivered as intermediate products to other quantity centers. Subtracting these costs from total costs, we arrive at the final costs of a quantity center.

The inefficient costs for raw materials of the material losses remain at a quantity center and are disclosed as primary material costs, energy costs, system costs, and waste management costs (IS0, 2011; Schrack, 2016). The inefficient costs at a quantity center, which are related to the intermediate products received from other quantity centers, are disclosed as inefficient secondary costs. Summing the inefficient costs, we determine a quantity center's costs of the total material losses, while adding the costs of the four cost categories results in a quantity center's inefficient flow costs. Further differentiation of this material flow matrix is possible by disaggregating the inefficient costs of the material losses into the costs of the inefficiency factors waste and rejects.

For the subsequent development of decision-useful information at the product unit level, we need to allocate the efficient and inefficient costs from quantity centers to product units in cost unit accounting. The general procedure to obtain this information is known from the material flow model, where we calculated the efficient total internal demand coefficient using (15) and the inefficient material demand per product unit with (17) and (18). Accordingly, efficient unit costs can be determined by dividing the efficient final costs of a quantity center in the material flow cost matrix by the production volume as the sum of the product's sales volume and inventory changes. The inefficient unit costs are calculated in two steps: in the first step, a quantity center's cost allocation rate is determined by the quotient of the total costs of the material losses and the production volume. In the second step, inefficient product unit costs are obtained by adding the products of the total internal demand coefficients and cost allocation rates over all quantity centers. Finally, product unit costs are computed by adding the efficient and inefficient product unit costs.

To support management with useful information for different purposes at the product unit level, cost unit accounting can be structured in different ways using the dimensions of cost category, inefficiency factor, and quantity center. To provide information about the relevance of a particular cost category, efficient and inefficient product unit costs can be disaggregated into cost categories, as seen in Table 2. To get more detailed information on inefficient product unit costs, the cost categories can be further disaggregated using the other two dimensions.

	efficient material costs per product unit
+	efficient energy costs per product unit
+	efficient system costs per product unit
=	**efficient product unit costs (1)**
	inefficient material costs per product unit
+	inefficient energy costs per product unit
+	inefficient system costs per product unit
+	inefficient waste management costs per product unit
=	**inefficient product unit costs (2)**
	product unit costs (1 + 2)

Table 2: Cost category-oriented product unit costing calculation scheme

If the economic consequences of the inefficiency factors are more relevant for management, then the order of the dimensions must be changed. In this case, inefficient product unit costs should first be disaggregated into waste- and reject-related product unit costs, as seen in Table 3. Such an inefficiency factor-oriented calculation scheme provides the economic impacts of each inefficiency factor on product unit costs. To get additional information regarding the place of their emergence and the proportions of the cost categories, inefficient unit costs of the inefficiency factors can be further disaggregated using the other two dimensions.

	efficient material costs per product unit
+	efficient energy costs per product unit
+	efficient system costs per product unit
=	**efficient product unit costs (1)**
	waste-related product unit costs
+	reject-related product unit costs
=	**inefficient product unit costs (2)**
	product unit costs (1 + 2)

Table 3: Inefficiency factors-oriented product unit costing calculation scheme

If management wants to know the amount of product unit costs caused by activities in a particular quantity center, efficient and inefficient product unit costs should first be disaggregated into the costs of the different quantity centers. This structure of product unit costs, as shown in Table 4, provides information about the responsibility of quantity center managers, which is also useful for influencing them to take actions to reduce material losses. Additionally, the costs for each quantity center can be disaggregated using the dimensions of the cost categories and inefficiency factors to reveal more detailed information.

	efficient product unit costs in the first quantity center
+	⋮
+	efficient product unit costs in the last quantity center
=	**efficient product unit costs (1)**
	inefficient product unit costs in the first quantity center
+	⋮
+	inefficient product unit costs in the last quantity center
=	**inefficient product unit costs (2)**
	product unit costs (1 + 2)

Table 4: Quantity center-oriented product unit costing calculation scheme

The flexible structure of this calculation scheme in MFCA provides management with relevant cost information about the economic consequences of material losses at the product unit level. Because the cost information so far is not provided either by MFCA or other cost accounting systems, product unit costing is an important extension of MFCA.

2.3.2 Material flow cost accounting system as a marginal cost accounting system

The purpose of MFCA is identification, measurement, and valuation of the material and energy flows in production processes (ISO, 2011). Therefore, in section 2.3.1, we determined efficient and inefficient costs at the quantity center and product unit level. However, some of these costs are not directly related to sales volume and changes in inventories. Consequently, knowledge of how management's short-term actions influence material losses is limited. To identify the relevant costs for short-term decisions, a further subdivision of efficient and inefficient costs into their variable and fixed components is necessary (Schmidt et al., 2015). Nevertheless, the structure of MFCA as a marginal cost accounting system follows in general that of the full cost accounting system from section 2.3.1, but some adjustments are necessary.

In quantity centers, the planned costs of the different cost types need to be subdivided into variable and fixed costs by analyzing their behavior in relation to changes in the cost driver levels using production and cost analysis techniques (Ewert and Wagenhofer, 2014; Kilger et al., 2012). Afterwards, variable and fixed costs are further subdivided into their efficient and inefficient components as described in section 2.3.1. Fixed inefficient costs occur to maintain a quantity center's ability to treat waste and dispose material losses, whereas fixed efficient costs occur to maintain the quantity center's ability to transform inputs to outputs. Variable efficient and inefficient costs are directly related to the material and energy flows in a quantity center and can be derived based on the material flow model. Subsequently, variable and fixed efficient and inefficient costs are assigned to the cost categories of material costs, energy costs, system costs, and waste management costs.

In the material flow cost matrix, only the variable efficient product costs are allocated to the intermediate product receiving quantity centers. Consequently, the fixed efficient costs remain with the costs of the material losses in the delivering quantity centers. Afterwards, the cost allocation rates for variable efficient and inefficient costs are determined. Using these cost allocation rates, variable efficient and inefficient costs are attributed to the different product units and, in the end, we obtain the variable product unit costs.

2.4 Conclusion

Because sustainability management is becoming increasingly important for companies, there is an additional need for information regarding the ecological consequences of their business activities. In this regard, MFCA, which aims to improve transparency of material flows and energy consumption in companies, can be a helpful accounting tool for management. However, until now, this instrument has only been used in some industries to analyze companies' current costs and not for budgeting efficient and inefficient costs. Thus, the main contribution of this paper is the development of a production and cost theory-based MFCA system, which can be used as a cost planning tool for any production process.

The basis of MFCA is a material flow model that considers the main inefficiency factors waste and rejects. This model is suitable for planning efficient and inefficient material demand for quantity centers as well as for product units, depending on sales volume and changes in inventory. Additionally, inefficient material demand at quantity center and product unit levels can be split into the material demand of waste and rejects. Based on the material flow model, we described in detail the design of MFCA as a full cost accounting system for budgeting costs. To overcome the barriers for widespread implementation of MFCA in practice, we clarified its relationship to other cost accounting systems. In particular we explained the budgeting process of cost types in quantity centers and their subdivision into efficient and inefficient costs as well as their aggregation to cost categories, so that MFCA can be easily integrated into other cost accounting systems. Moreover, we described the use of the material flow cost matrix in any production process, and we extended MFCA by a flexible cost unit accounting with the dimensions of cost category, efficiency factor, and quantity center. Finally, we explained the design of MFCA as a marginal cost accounting system, which provides relevant information for short-term decisions.

In this paper we focused on the use of MFCA in one company. Nevertheless, this accounting system can also be used as a whole or in parts for the analysis of a value chain (Nakajima et al., 2015, Schrack, 2016). Additionally, with its material flow model, MFCA can be connected to other environmental accounting instruments like virtual water or carbon footprint accounting (Bagliani and Martini, 2012, Günther, 2008; Schmidt, 2015; Shao and Chen, 2016). Moreover, other cost drivers of the inefficient material demand, such as recycling, reworking, and production intensity, can be taken into account in the material flow model as well as in MFCA. Other promising future research fields might be the additional consideration of external effects (Schrack, 2016) and integration of MFCA into life cycle costing, so that all ecological consequences can be measured across the whole life cycle of products.

3. Material Flow Cost Accounting with Multiple Inefficiency Factors

Stefan Dierkes and David Siepelmeyer

Abstract

The introduction of closed material and energy loops is a major issue for companies to improve their resource efficiency and requires detailed information on the level, composition, and associated costs of their entering and leaving material flows. To provide sustainability management with the relevant information, we develop a production theory-based material flow model that considers the impact of waste, rejects, reworking, and recycling on the material demand at the company, quantity center, and product unit levels. Furthermore, we design a material flow cost accounting system calculating the manufacturing, recycling, and disposal quantity center costs as well as product unit costs. Finally, we discuss the consequences of using the material distribution key in material flow cost accounting and identify further development opportunities of this accounting system.

Keywords

Material flow cost accounting, Material flow model, Reworking, Recycling,
Resource efficiency

JEL-Classification

Q56

3.1 Introduction

The increasing scarcity of major materials and the serious environmental impact of corporate manufacturing have brought public attention to the environmental performance of companies. Companies strive to improve their resource efficiency by introducing different recycling measures for the establishment of closed material loops, which require detailed information about the level and composition of their entering and leaving material flows with their monetary consequences (Aguilar Esteva et al., 2021; Prosman et al., 2017; Schmidt, 2005). An environmental cost accounting system suitable for this purpose is material flow cost accounting (MFCA). It measures the quantities and costs of the material flows inside a company and separately determines the costs of the products from those of the material and product losses (Kawalla et al., 2018; Kitada et al., 2022; Nishimura et al., 2021). However, it lacks of a production theory-based material flow model that can predict the material demand of a company in dependence on central influencing factors, such as waste, reject, or recycling. Accordingly, most papers on MFCA do not distinguish between the reasons for material and product loss creation and reduction, preventing a differentiated analysis of the economic and environmental impacts of a company's environmental burdens and recycling measures (ISO, 2011; Schmidt and Nakajima, 2013; Wan et al., 2015). Furthermore, MFCA uses the material distribution key to allocate costs to products and material losses, resulting in unclear consequences on cost allocation and difficulties for the integration of MFCA into other cost accounting systems (Günther et al., 2015; Wagner, 2015).

For these reasons, we design a material flow-oriented environmental cost accounting system that provides sustainability management with detailed cost information on a company's environmental impacts and environmental protection measures. It considers the effects of waste, rejects, reworking, and recycling on the material demand and thus enables a differentiated analysis of the material flows at the company, quantity center, and product unit levels. We use the material flow model to design an MFCA system and describe its application for budgeting manufacturing, recycling, and disposing quantity center costs and determining product unit costs. Furthermore, we analyze the consequences and possible alternatives to using the material distribution key.

MFCA is one of the most promising environmental cost accounting tools that separates the costs of the products from those of the materials and product losses (Behnami et al., 2019; ISO, 2011; Yagi and Kokubu, 2019). The costs of the products include all costs that become a physical part of a company's intended products, whereas the costs of the material and product losses encompass all costs that can be directly or indirectly traced back to the creation and treatment of unintended co-products. Despite its features and potential benefits for sustainability management, MFCA is rarely implemented in corporate practice (see e.g. Bux and Amicarelli, 2022, Dekamin and Barmaki, 2018, and May and Günther, 2020). Kokubu and Kitada (2015) and Sulong et al. (2015) analyzed the reasons for the limited application. They identify multiple facilitating and complicating factors that influence a company's successful introduction of this environmental cost accounting tool, such as team cooperation, lack of technical knowledge, and training. However, the limited use of MFCA is not only due to company-specific factors but also to some general factors. First, it uses terms, such as cost categories, quantity centers, or the material distribution key that are not used in other environmental cost accounting systems (Nakajima, 2004; Nishitani et al., 2022). Second, the accounting system is only implemented on a project basis in small companies with comparatively simple production processes (Günther et al., 2015; ISO, 2011; Schrack, 2016). Accordingly, it is unclear how it can be applied in big corporations with complex production processes. Third, its focus is primarily on the costs of the materials and product losses, whereas their causes remain unclear (ISO, 2011; Schmidt et al., 2015). However, environmental cost accounting tools should identify the cost drivers of these losses as starting points for forecasting and improving a company's economic and environmental performance. For this purpose, MFCA requires a production theory-based material flow model as known from other environmental cost accounting systems and recycling management.

Keilus (1993) develops an environmental cost accounting system for determining the product unit costs considering waste, rejects, reworking, and recycling without separating the influencing factors on cost center and product unit levels. Letmathe (1998) categorizes the environmental impact that results from corporate manufacturing and develops a production model for their quantitative measurement. He calculates the costs of the environmental impacts and shows the general integration of these costs into a cost accounting system. Kloock and Schiller (1997) explain the structure and application of marginal costing and activity-based costing. They develop a production theory-based material flow model for cost budgeting. However, in all these studies, the costs of the material and product losses are neither disclosed at the cost center nor the product unit level. Spengler et al. (1997) provide a formal model for the planning of the dismantled and recycled components from demolition waste and byproducts from the steel industry, whereas Schmidt (2005) uses a material flow model to predict material flows in complex production processes in a company in the e-waste recycling industry. Nevertheless, these models also do not provide information on the drivers of material and product losses and are, therefore, unsuitable for a differentiated cost forecast.

So far, only Dierkes and Siepelmeyer (2019) have used a material flow model to develop a forward-looking MFCA system. Their system comprises waste and reject as inefficiency factors, and they analyze the effects on the material demand on quantity center and product unit levels, as well as the costs of the products and the material and product losses. However, they do not consider the effects of reworking and recycling. In addition, their basic material flow model is unsuitable for integrating reworking and recycling because it needs a more precise separation of the material demands resulting from the various inefficiency factors.

To overcome the above described theoretical and practical shortcomings, we develop an MFCA system that pays particular attention to the costs of a company's environmental impacts and environmental protection measures. We design a material flow model considering the effects of waste, rejects, reworking, and recycling on the material demand. Moreover, we analyze the creation and reduction of the material and product losses in manufacturing, recycling, and disposal quantity centers as well as on the product unit level. In addition, we develop an MFCA system to determine the impacts of a company's inefficiency factors and environmental protection measures on the costs of the products and the material and product losses. Here we also explain the budgeting of manufacturing, recycling, and disposal quantity center costs and a flexibly designed calculation of product unit costs depending on the information needs of sustainability management. Finally, we discuss the consequences of using the material distribution key in MFCA and further development opportunities.

This paper is structured as follows: In the second chapter, we design a material flow model for the determination of the material demand of a company and analyze the corresponding material flows. The third chapter deals with the development of an MFCA system for the budgeting of the quantity center costs and the determination of the product unit costs. The paper concludes in chapter four with the main results and an outlook for future research.

3.2 Material flow model

3.2.1 Overview of corporate transformation processes

A manufacturing company converts materials and intermediate products into products in multi-stage transformation processes, which also results in material and product losses (Aguilar Esteva et al., 2021; Bhimani et al., 2019; Datar and Rajan, 2018). While the products are sold to customers, the others have no economic value to a company and consist of different liquid, gaseous, and solid materials and product loss types. The single physical transformation processes are executed in quantity centers and the cost centers of a company usually encompass multiple quantity centers (Dierkes and Siepelmeyer, 2019; ISO, 2011; Schrack, 2016). Due to our focus on the creation and reduction of material and product losses, we only analyze the material flows of the manufacturing, recycling, and disposal quantity centers.

Manufacturing quantity centers produce a company's products. Their input includes materials and intermediate products, whereas the output consists of the provisional material and product waste as well as the provisional production yield and the provisional rejects. Waste summarizes all untransformed materials and intermediate products of a manufacturing process that do not become a physical part of the product (Keilus, 1993; Kloock and Schiller, 1997; Letmathe, 1998). The provisional production yield consists of faultlessly manufactured products, whereas the provisional rejects are products that do not meet the predefined quality requirements. Some rejects with minor product defects can be reworked with the additional use of materials and intermediate products to meet the quality requirements. We assume that the product defects are immediately detected after the manufacturing process and are eliminated in the same manufacturing quantity center (Kilger et al., 2012; Krüger, 1959).[1] By adding the reworked products and the provisional production yield, we obtain the final production yield that can be used for sale or as input into other manufacturing quantity centers. The rejects with severe product defects are denoted as final rejects that belong with the provisional material and product waste to the material and product losses of a manufacturing quantity center (Chompu-inwai et al., 2015; Schmidt, 2005; Schrack, 2016).

[1] The material flow model can be easily adjusted in the case of separate reworking quantity centers.

The provisional material and product waste as well as the final rejects cannot be directly reused in manufacturing quantity centers. To recover at least some of these materials and intermediate products, companies implement recycling processes. We only consider a company's internal recycling and assume a separate **recycling quantity center** for each material and product loss type. Here we must take into account the additional recycling-related material and product demand (Keilus, 1993; Kilger et al., 2012; Schmidt, 2005). The output of the recycling quantity centers consists of the recovered materials and products re-entering the transformation processes as well as the material and product losses.

The material and product losses are discarded in separate material and product disposing quantity centers. The input of a **disposal quantity center** includes an additional disposal-related demand for materials besides the material or product losses. The discarded materials and products are the output of the disposing quantity centers. The structure of the transformation processes is illustrated in Figure 7.

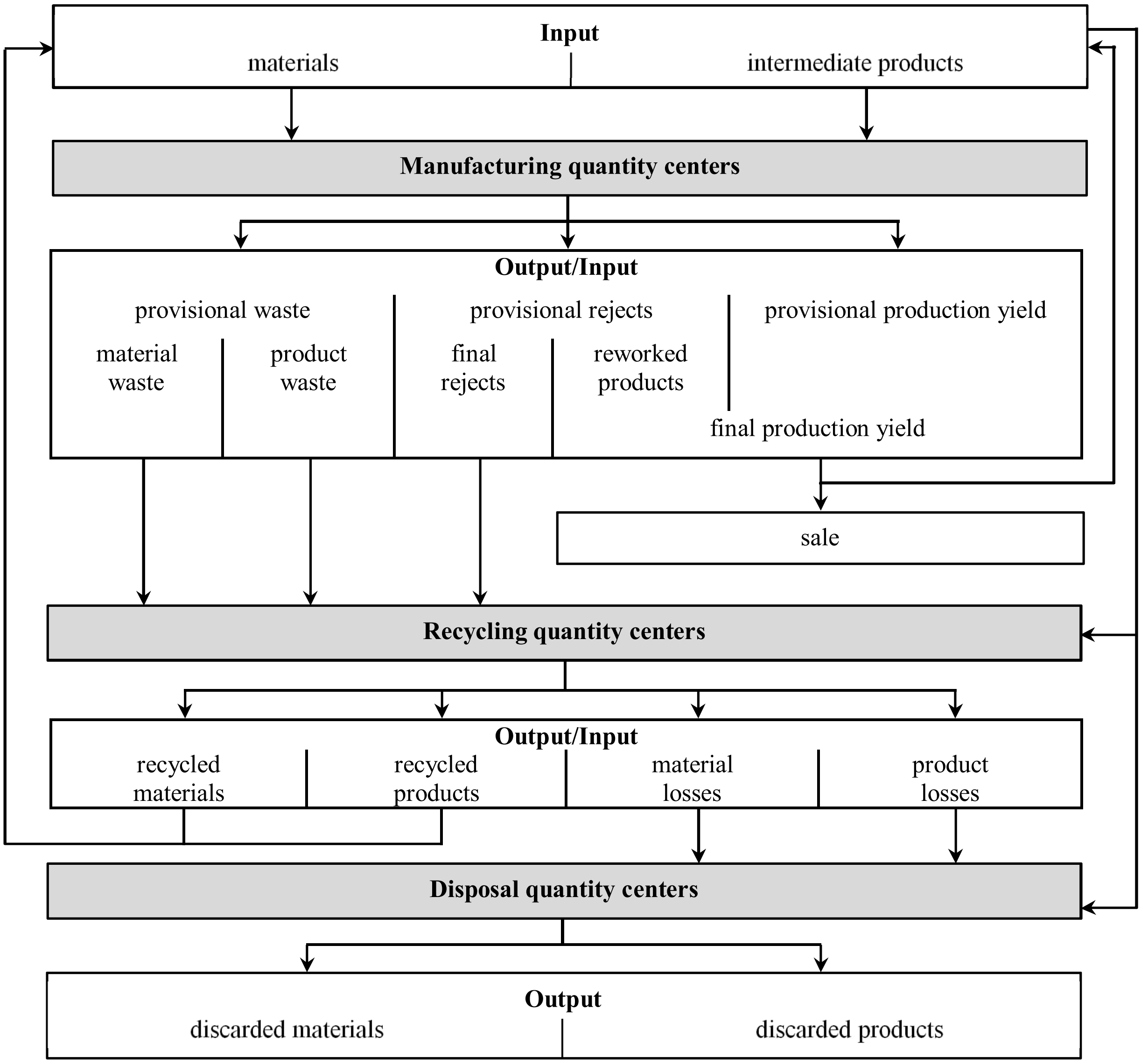

Figure 7: Corporate transformation processes

After describing the transformation processes, we develop a production theory-based material flow model to determine the efficient material demand of a company.

3.2.2 Development of a material flow model without inefficiency factors

Efficient material demand is characterized by the absence of material and product losses in the transformation processes (Dierkes and Siepelmeyer, 2019; ISO, 2011). It represents a company's demand for materials and products directly related to the production of the intended products. Accordingly, it is unnecessary to include the effects of waste, rejects, reworking, and recycling into a material flow model to determine the efficient material demand and we only have to consider the material demand of the manufacturing quantity centers.

In manufacturing quantity centers enter $m = 1,\ldots,M$ materials for manufacturing $j = 1,\ldots,J$ products, whereby each manufacturing quantity center produces only one product. Therefore, j can be used not only as a product but also as a quantity center index. The direct production coefficient $a'_{m,j}$ represents the efficient demand for material m used to manufacture one unit of product j. In addition to this primary material demand, manufacturing quantity centers need intermediate products denoted as secondary material demand (Dörner, 1984; Keilus, 1993; Schiller and Kloock, 1997). The direct production coefficient $a'_{s,j}$ indicates the efficient demand for intermediate products required for manufacturing one unit of product j, whereby s is another product and quantity center index. A quantity center's primary and secondary material demand depends on the sales volume xa_j of product j. Thus, we can calculate the efficient material and product demand rm'_m and rp'_j as follows (Boons, 1998; Fandel et al., 2009; Kloock and Schiller, 1997):

$$rm'_m = \sum_{s=1}^{J} a'_{m,s} \cdot rp'_s \qquad \text{with m=1,...,M} \qquad (19)$$

$$rp'_j = \sum_{s=1}^{J} a'_{j,s} \cdot rp'_s + xa_j \qquad \text{with j = 1,...,J} \qquad (20)$$

We refrain from additionally integrating inventory changes of materials and products as well as sales volumes of materials into the equation system to keep the following analysis as simple and understandable as possible (see for the integration e.g. Dierkes and Siepelmeyer, 2019). To solve (19) and (20), we transform the equation system into a matrix notation. The symmetrical matrix $\underline{A}'$ represents the efficient direct production coefficients and has the dimensions $M + J$ times $M + J$. In (21), the column vectors $\underline{xa}$ and $\underline{r}'$ denote the sales volume and the efficient material demand (Fandel et al., 2009; Kloock and Schiller, 1997):

$$\underline{r}' = \underline{A}' \cdot \underline{r}' + \underline{xa} \qquad (21)$$

Using the unity matrix $\underline{E}$ to solve for the matrix of the efficient material demand, we also obtain the matrix of the efficient total production coefficients $\underline{B}'$:

$$\underline{r}' = (\underline{E} - \underline{A}') \cdot \underline{xa} = \underline{B}' \cdot \underline{xa} \tag{22}$$

In the following, we have to incorporate the inefficiency factors into the material flow model resulting in material and product losses.

3.2.3 Development of a material flow model with multiple inefficiency factors and environmental protection measures

One option to include the inefficiency factors waste and reject into the material flow model is to add the corresponding effects to the efficient direct production coefficients (Dierkes and Siepelmeyer, 2019; Keilus, 1993). However, with the integration of reworking and recycling, this procedure becomes too complex and unsuitable for separate disclosure of the material demand increasing and decreasing effects. Therefore, we need a more differentiated material flow model that provides information on the material flows of the single inefficiency factors and environmental protection measures.

The starting point for the development of the material flow model is the efficient material demand coefficients $a'_{m,s}$ that are multiplied with a company's production volume rp_s. The quantity of provisional material waste rwm_m increases the demand for material m, whereas the quantity of recycled materials rcm_m has a reducing impact on the primary material demand, as illustrated in Figure 7. This results in the adjusted material demand rm_m:

$$rm_m = \sum_{s=1}^{J} a'_{m,s} \cdot rp_s + \underbrace{rwm_m}_{\substack{\text{provisional}\\\text{material waste}}} - \underbrace{rcm_m}_{\text{recycled materials}} \qquad \text{with } m = 1,\dots,M \tag{23}$$

The inefficiency factors waste and reject as well as the environmental protection measures reworking and recycling, have different effects on the adjusted product demand rp_j. The quantities of the provisional product waste and provisional rejects rwp_j and rv_j increase the product demand, while the quantities of the reworked and recycled products rn_j and rcp_j have a reducing effect:

$$rp_j = \sum_{s=1}^{J} a'_{j,s} \cdot rp_s + \underbrace{rwp_j}_{\substack{\text{provisional}\\ \text{product waste}}} + \underbrace{rv_j}_{\substack{\text{provisional}\\ \text{rejects}}} - \underbrace{rn_j}_{\substack{\text{reworked}\\ \text{products}}} - \underbrace{rcp_j}_{\substack{\text{recycled}\\ \text{products}}} + xa_j \qquad \text{with } j=1,\ldots,J \tag{24}$$

To calculate the quantities of the provisional material and product waste, we determine the waste-related direct production coefficients $\alpha_{m,j}$ and $\alpha_{s,j}$ representing the waste-related demand for material m and intermediate product s caused by the production of one unit of product j (Dierkes and Siepelmeyer, 2019; Dörner, 1984; Keilus, 1993):

$$rwm_m = \sum_{s=1}^{J} \alpha_{m,s} \cdot rp_s \qquad \text{with } m = 1,\ldots,M \tag{25}$$

$$rwp_j = \sum_{s=1}^{J} \alpha_{j,s} \cdot rp_s \qquad \text{with } j = 1,\ldots,J \tag{26}$$

Rejects have a wide range of product defects differing in frequency and scope. We assume an average reject rate β_j representing the proportion of the production quantity with slight to severe product defects. Considering the production volume of product j, we obtain the quantity of the provisional rejects rv_j (Dierkes and Siepelmeyer, 2019; Keilus, 1993):

$$rv_j = \beta_j \cdot rp_j \qquad \text{with } j = 1,\ldots,J \tag{27}$$

For calculating the quantity of reworked products $rn_{m,j}$, we use the reworking rate τ_j as the proportion of reworked products to provisional rejects. The remaining final rejects ra_j cannot be reworked for technological or economic reasons and are forwarded to the recycling quantity centers (Kilger et al., 2012; Letmathe, 1998; Schmidt, 2005):[2]

$$rn_j = \tau_j \cdot rv_j \qquad \text{with } j = 1,\ldots,J \qquad (28)$$

$$ra_j = (1-\tau_j) \cdot rv_j \qquad \text{with } j = 1,\ldots,J \qquad (29)$$

The provisional material and product waste rwm_m and rwp_j as well as the final reject ra_j are treated in the recycling quantity centers in two steps. In a first step, the provisional product waste and final rejects are decomposed to the value added stage, where their bound materials and products are reusable. The direct production coefficients $a'_{m,j}$ and $a'_{s,j}$ represent the quantity of material m and intermediate product s that are recovered from a single decomposition stage of product j, whereby the direct product coefficients are deducted from the products' parts lists and decomposition structure. Summing the quantities of the recovered material m and product s from all decomposition stages, we obtain the recycling-related direct production coefficients $a^{\lambda}_{m,j}$ and $a^{\lambda}_{s,j}$. Based on the recycling-related direct production coefficients, we can calculate the quantities of the reusable material m and product j rum_m and rup_j from the provisional product waste rwp_s and the final rejects ra_s:

$$rum_m = \sum_{s=1}^{J} a^{\lambda}_{m,s} \cdot (rwp_s + ra_s) \qquad \text{with } m = 1,\ldots,M \qquad (30)$$

$$rup_j = \sum_{s=1}^{J} a^{\lambda}_{j,s} \cdot (rwp_s + ra_s) \qquad \text{with } j = 1,\ldots,J \qquad (31)$$

In the second step, reusable materials and products as well as material waste are subject to recycling processes. The recycling rate λ_m and λ_j determine the share of material m and product j that is recycled from the reusable materials, the provisional material waste, and the reusable

2 The reworking-related material and product demand can be additionally considered in (23) and (24). To keep the equations simple, we take this additional demand at quantity center level into account.

products (Keilus, 1993; Kilger et al., 2012; Letmathe, 1998). The remaining material and product losses are discarded in disposal quantity centers, as shown in Figure 7. We can determine the quantities of the recycled materials and products rcm_m and rcp_j as well as the disposed materials and products rvm_m and rvp_j depending on the recycling rates:[3]

$$rcm_m = \lambda_m \cdot (rum_m + rwm_m) \qquad \text{with } m = 1,\ldots,M \qquad (32)$$

$$rcp_j = \lambda_j \cdot rup_j \qquad \text{with } j = 1,\ldots,J \qquad (33)$$

$$rvm_m = (1-\lambda_m) \cdot (rum_m + rwm_m) \qquad \text{with } m = 1,\ldots,M \qquad (34)$$

$$rvp_j = (1-\lambda_j) \cdot rup_j \qquad \text{with } j = 1,\ldots,J \qquad (35)$$

With equations (23) to (35), we obtain an equation system that we transform into a matrix notation for its solution. The symmetrical matrix $\underline{A}$ represents the matrix of the adjusted direct production coefficients and possesses the dimension $5 \cdot M + 8 \cdot J$ times $5 \cdot M + 8 \cdot J$:

$$\underline{r} = \underline{A} \cdot \underline{r} + \underline{xa} \qquad (36)$$

If we solve for the matrix of the adjusted material demand $\underline{r}$, we additionally obtain the matrix of the adjusted total material demand coefficients $\underline{B}$:

$$\underline{r} = \underline{A} \cdot \underline{r} + \underline{xa} = \underline{B} \cdot \underline{xa} \qquad (37)$$

Changes in inventories for the provisional rejects, reworked products, or recycled materials and products can be integrated by adding a corresponding column vector to (36). However, according to the determination of the efficient material demand, we forgo their integration into the material flow model. Using the material flow models from this and the last chapter, we know a company's efficient and adjusted material demand. Hence, we can determine the inefficient

3 We plan the additional recycling- and disposal-related material and product demand at quantity center level, like the one for reworking.

material demand v_m of material m if we subtract the efficient material demand from the adjusted one (Dierkes and Siepelmeyer, 2019):

$$v_m = rm_m - rm'_m \qquad \text{with } m = 1,\ldots,M \qquad (38)$$

However, to determine the isolated impact of waste, reject, reworking, and recycling in the quantity centers on the material demand, we need to analyze the entering and leaving material flows of the quantity centers.

3.2.4 Analysis of the material demand at quantity center level

To identify the effects of a quantity center on material and product losses, we subdivide its material demand into three categories: efficient, inefficient, and inefficiency decreasing. In the first step, we use product-oriented input-output tables disclosing the demand for materials and intermediate products. However, in MFCA, the focus is on the material flows regardless of their value added stage. Therefore, in the second step, we convert the product-oriented input-output tables into material-oriented ones to determine the entering and leaving material flows of a quantity center. According to the sequence of the corporate transformation processes, as shown in Figure 7, we start with analyzing the input and output of the manufacturing quantity centers.

The input of a ***manufacturing quantity center*** consists of materials denoted as primary demand $rm^{M,p}_{m,j}$ and the obtained intermediate products $rp_{s,j}$ that represent the secondary demand. The primary demand is determined by multiplying the sum of the efficient and waste-related direct production coefficients from (23) and (25) with the production quantity of product j. For the calculation of the secondary demand, we assume that the inefficiency factors occur only in the analyzed quantity center, whereas the processes in all other quantity centers are efficient (Dierkes and Siepelmeyer, 2019). Consequently, we can determine the material and product losses caused by the transformation processes of a quantity center. The output of manufacturing quantity center j consists of products and rejects as well as the provisional material and product waste. The quantities of the products and rejects can be directly observed from the material flow model, whereby these figures can be further subdivided into the sales volume, intermediate products, provisional rejects, reworked products, and final rejects, as illustrated in Table 5. The quantities of the provisional material and product waste have to be calculated separately by multiplying the waste-related direct production coefficients from (25) and (26) with the production quantity of manufacturing quantity center j.[4]

Input			Output	
Materials			**Products**	
$m = 1,\dots,M$	$rm^{M,p}_{m,j}$		Sales volume	xa_j
Intermediate products		+	Intermediate products	$(rp_j - ra_j) - xa_j$
$s = 1,\dots,J$	$rp_{s,j}$	=	Final production yield	$rp_j - ra_j$
			Rejects	
			Provisional rejects	rv_j
		–	Reworked products	rn_j
		=	Final rejects	ra_j
			Provisional waste	
			Material $m = 1,\dots,M$	$rwm_{m,j}$
			Products $s = 1,\dots,J$	$rwp_{s,j}$

Table 5: Product-oriented input-output table of manufacturing quantity center j

To calculate the material flow of material m of a manufacturing quantity center, we transform the product-oriented input-output table into a material-oriented one. The primary material demand $rm^{M,p}_{m,j}$ of material m is already known from table 5, whereas the secondary material demand $rm^{M,s}_{m,j}$ of manufacturing quantity j has to be calculated separately. For this purpose, we multiply the quantity of the obtained intermediate product $rp_{s,j}$ with the efficient total material demand coefficient $b'_{m,s}$. We can calculate the input $rm^{M}_{m,j}$ of material m into manufacturing quantity center j (Dierkes and Siepelmeyer, 2019):

4 The product-oriented input-output table can be expanded if the additional reworking-related material and product demand are integrated into the material flow model.

$$\mathrm{rm}_{m,j}^{M} = \mathrm{rm}_{m,j}^{M,p} + \mathrm{rm}_{m,j}^{M,s} = \underbrace{(a'_{m,j} + \alpha_{m,j}) \cdot \mathrm{rp}_j}_{\text{primary material demand}} + \underbrace{\sum_{s=1}^{J} b'_{m,s} \cdot \underbrace{(a'_{s,j} + \alpha_{s,j}) \cdot \mathrm{rp}_j}_{\mathrm{rp}_{s,j}}}_{\text{secondary material demand}} \tag{39}$$

To determine the increasing and decreasing impacts of a manufacturing quantity center's output, we subdivide the material demand of material m into an efficient, inefficient, and inefficiency decreasing one. We start with the calculation of the efficient material demand $\mathrm{rm}_{m,j}^{M,e}$ that includes only the faultlessly manufactured products and thus no waste or reject:

$$\mathrm{rm}_{m,j}^{M,e} = \underbrace{a'_{m,j} \cdot (\mathrm{rp}_j - \mathrm{rv}_j)}_{\text{primary material demand}} + \underbrace{\sum_{s=1}^{J} b'_{m,s} \cdot a'_{s,j} \cdot (\mathrm{rp}_j - \mathrm{rv}_j)}_{\text{secondary material demand}} \tag{40}$$

If we subtract (40) from (39), we receive the inefficient material demand $v_{m,j}^{M}$ that consists of the provisional material and product waste as well as the provisional rejects. To reveal the impacts of the reworking activities on the material demand, we replace the provisional rejects rv_j by the sum of the final rejects ra_j and reworked products rn_j. Thus, we can separately disclose the effects of waste and final reject $v_{m,j}^{\alpha}$ and $v_{m,j}^{\beta}$ as well as for reworking $v_{m,j}^{\tau}$ denoted as inefficiency decreasing material demand:

$$\begin{aligned} v_{m,j}^{M} &= \underbrace{\alpha_{m,j} \cdot \mathrm{rp}_j}_{\substack{\text{provisional}\\ \text{material waste}}} + \underbrace{\sum_{s=1}^{J} b'_{m,s} \cdot \alpha_{s,j} \cdot \mathrm{rp}_j}_{\substack{\text{provisional}\\ \text{product waste}}} + \underbrace{a'_{m,j} \cdot (\mathrm{ra}_j + \mathrm{rn}_j) + \sum_{s=1}^{J} b'_{m,s} \cdot a'_{s,j} \cdot (\mathrm{ra}_j + \mathrm{rn}_j)}_{\text{provisional rejects}} \\ &= \underbrace{\alpha_{m,j} \cdot \mathrm{rp}_j + \sum_{s=1}^{J} b'_{m,s} \cdot \mathrm{rwp}_{s,j}}_{\text{waste-related material loss}} + \underbrace{a'_{m,j} \cdot \mathrm{ra}_j + \sum_{s=1}^{J} b'_{m,s} \cdot a'_{s,j} \cdot \mathrm{ra}_j}_{\text{final reject-related material loss}} + \underbrace{a'_{m,j} \cdot \mathrm{rn}_j + \sum_{s=1}^{J} b'_{m,s} \cdot a'_{s,j} \cdot \mathrm{rn}_j}_{\text{reworking-related material savings}} \\ &= v_{m,j}^{\alpha} + v_{m,j}^{\beta} + v_{m,j}^{\tau} \end{aligned} \tag{41}$$

With equations (39) to (41), we can calculate for manufacturing quantity center j a material-oriented input-output table for material m, as illustrated in Table 6.

Input		Output	
Primary material demand	$rm^{M,p}_{m,j}$	**Efficient material demand**	
Secondary material demand	$rm^{M,s}_{m,j}$	+ Provisional production yield	$rm^{M,e}_{m,j}$
		Inefficiency decreasing material demand	
		+ Reworked products	$v^{\tau}_{m,j}$
		Inefficient material demand	
		+ Final rejects	$v^{\beta}_{m,j}$
		+ Provisional waste	$v^{\alpha}_{m,j}$
Material demand	$rm^{M}_{m,j}$	Material demand	$rm^{M}_{m,j}$

Table 6: Material-oriented input-output table of manufacturing quantity center j

The losses of the manufacturing quantity centers are forwarded to the recycling quantity centers. In the ***product recycling quantity center j*** enter the provisional product waste rwp_j and the final reject ra_j of product j from all manufacturing quantity centers. These quantities can be directly obtained from the material flow model. The output consists of the recycled material m and product s $rcm_{m,j}$ and $rcp_{s,j}$ as well as the material and product losses $rvm_{m,j}$ and $rvp_{s,j}$, which can be calculated based on the recycling-related material demand coefficients $a^{\lambda}_{m,j}$ and $a^{\lambda}_{s,j}$ as well as the recycling rates λ_m and λ_s:

$$rcm_{m,j} = \lambda_m \cdot a^{\lambda}_{m,j} \cdot (rwp_j + ra_j) \qquad \text{with } m = 1,\ldots,M \qquad (42)$$

$$rcp_{s,j} = \lambda_s \cdot a^{\lambda}_{s,j} \cdot (rwp_j + ra_j) \qquad \text{with } s = 1,\ldots,J \qquad (43)$$

$$rvm_{m,j} = (1-\lambda_m) \cdot a^{\lambda}_{m,j} \cdot (rwp_j + ra_j) \qquad \text{with } m = 1,\ldots,M \qquad (44)$$

$$rvp_{s,j} = (1-\lambda_s) \cdot a^{\lambda}_{s,j} \cdot (rwp_j + ra_j) \qquad \text{with } s = 1,\ldots,J \qquad (45)$$

The product-oriented input-output table of the product recycling quantity center j is illustrated in Table 7.[5]

[5] The product-oriented input-output table can be expanded if the additional recycling-related material and product demand are integrated into the material flow model.

Input		Output	
Provisional product waste	rwp_j	**Recycled**	
Final rejects	ra_j	Products $s = 1,\dots,J$	$rcp_{s,j}$
		Materials $m = 1,\dots,M$	$rcm_{m,j}$
		Losses	
		Products $s = 1,\dots,J$	$rvp_{s,j}$
		Materials $m = 1,\dots,M$	$rvm_{m,j}$

Table 7: Product-oriented input-output table of product recycling quantity center j

To calculate the input $rm^{RP}_{m,j}$ of material m, we multiply the quantities of the provisional product waste and final rejects with the efficient total material demand coefficient $b'_{m,j}$. The product recycling quantity center's output includes an inefficiency decreasing and inefficient material demand. The recycled products and materials belong to the inefficiency decreasing material demand, whereas the product and material losses represent the inefficient one. The material flows of the recycled product s $rcpm_{m,s,j}$ and the loss of product s $rvpm_{m,s,j}$ are calculated by multiplying (43) and (45) with the efficient total material demand coefficient $b'_{m,s}$, whereas the recycled materials and the material losses are already known from Table 7. The corresponding material-oriented input-output table of the product recycling quantity center j is illustrated in Table 8.

Input		Output	
Secondary material demand	$rm^{RP,s}_{m,j}$	**Inefficiency decreasing material demand**	
		+ Recycled products s=1,…,J	$rcpm_{m,s,j}$
		+ Recycled materials	$rcm_{m,j}$
		Inefficient material demand	
		+ Loss products s=1,…,J	$rvpm_{m,s,j}$
		+ Loss materials	$rvm_{m,j}$
Material demand	$rm^{RP}_{m,j}$	Material demand	$rm^{RP}_{m,j}$

Table 8: Material-oriented input-output table of product recycling quantity center j

The input rm^{RM}_{m} of ***material recycling quantity center m*** includes only the material waste rwm_m. Its output can be subdivided with the recycling rate λ_m into the quantities of the recycled material rcm_m and the material losses rvm_m representing the inefficiency decreasing and inefficient material demand, as illustrated in Table 9.[6]

Input		Output	
Secondary material demand	$rm_m^{RM,s}$	**Inefficiency decreasing material demand**	
		+ Recycled material m	rcm_m
		Inefficient material demand	
		+ Loss material m	rvm_m
Material demand	rm_m^{RM}	Material demand	rm_m^{RM}

Table 9: Material-oriented input-output table of material recycling quantity center m

Afterwards, the material and product losses are discarded in separate ***disposal quantity centers*** with no further transformation processes. Therefore, we can turn to the determination of the material demand of product units.

3.2.5 Determination of the material demand at the product unit level

To calculate the material demand of a product unit, we need to allocate the material demand from the manufacturing, recycling, and disposal quantity centers to the product units. We start with allocating the efficient, inefficient, and inefficiency decreasing material demand of the manufacturing quantity centers. We can determine the efficient total material demand coefficient already known from chapter 3.2.2 by dividing the efficient material demand of ***manufacturing quantity center*** **j** by its provisional production yield (Dierkes and Siepelmeyer, 2019):

$$b'_{m,j} = \frac{rm_{m,j}^{M,e}}{rp_j - rv_j} \tag{46}$$

In a multi-stage transformation process, the production of product j occurs not only in manu-

[6] The additional recycling-related material and product demand can also be integrated into the material-oriented input-output table of the material recycling quantity center.

facturing quantity center j, but also in ***all other manufacturing quantity centers*** whose intermediate products go into product j. Therefore, we calculate a separate allocation rate for each manufacturing quantity center for waste, rejects, and reworking. The provisional waste-related allocation rate $ar^{\alpha}_{m,j}$ is calculated by dividing the waste-related material demand of a manufacturing quantity center by its production quantity. To provide separate information at the product unit level on the reject-related material losses and the reworking-related material savings, we calculate with $ar^{\beta+\tau}_{m,j}$ and $ar^{\tau}_{m,j}$ a provisional reject- and reworking-related allocation rate. The reject-related allocation rate represents the quantity of the provisional reject-related material losses without reworking. It is determined by dividing the sum of the final reject- and reworking-related material demand from (41) by the production quantity. In contrast, the reworking-related allocation rate discloses the material savings related to the reworking activities of a manufacturing quantity center. This allocation rate is calculated by dividing the reworking-related material demand of a manufacturing quantity center by its production quantity:

$$ar^{\alpha}_{m,j} = \frac{v^{\alpha}_{m,j}}{rp_j} \qquad ar^{\beta+\tau}_{m,j} = \frac{v^{\beta}_{m,j} + v^{\tau}_{m,j}}{rp_j} \qquad ar^{\tau}_{m,j} = \frac{v^{\tau}_{m,j}}{rp_j} \tag{47}$$

For the allocation of material demand of the ***product recycling quantity centers*** to the product units, we have to determine the recycled quantity of material m per unit of product j. Here we have to consider three components: First, the rejects of manufacturing quantity center j are recycled in the product recycling quantity center j. The recycled material demand can be calculated based on the recycling-related direct production coefficients $a^{\lambda}_{m,j}$ and $a^{\lambda}_{s,j}$, the efficient total material demand coefficient $b'_{m,s}$, and the recycling rates λ_m and λ_s. Second, the provisional product waste caused by the production of product j is recycled in product recycling quantity centers to recover materials and products. Third, the material waste m of manufacturing quantity center j is recycled in **material recycling quantity center m**, whereby the quantity of the recycled materials is determined by multiplying the recycling rate of material m with the provisional material waste of manufacturing quantity center j. If we sum up the three components of the recovered materials and products, we obtain with $v^{\lambda}_{m,j}$ the recycling-related material demand of manufacturing quantity center j:[7]

$$v^{\lambda}_{m,j} = \underbrace{\lambda_m \cdot a^{\lambda}_{m,j} \cdot ra_j + \sum_{k=1}^{J} b'_{m,k} \cdot \lambda_k \cdot a^{\lambda}_{k,j} \cdot ra_j}_{\text{product recycling quantity center j}}$$
$$+ \underbrace{\sum_{s=1}^{J} \lambda_m \cdot a^{\lambda}_{m,s} \cdot rwp_{s,j} + \sum_{s=1}^{J} \sum_{k=1}^{J} b'_{m,k} \cdot \lambda_k \cdot a^{\lambda}_{k,s} \cdot rwp_{s,j}}_{\text{product recycling quantity centers s=1,...,J}} \tag{48}$$
$$+ \quad \underbrace{\lambda_m \cdot rwm_{m,j}}_{\text{material recycling quantity center m}}$$

Dividing the recycling-related material demand by the production quantity of manufacturing quantity center j yield a recycling-related allocation rate $ar^{\lambda}_{m,j}$, which can be further disaggregated in separate allocation rates according to (48):

$$ar^{\lambda}_{m,j} = \frac{v^{\lambda}_{m,j}}{rp_j} \tag{49}$$

After calculating the waste-, reject-, reworking-, and recycling-related allocation rates, we can determine the material demand of a product unit. Taking the production relationships among the manufacturing quantity centers into account, we multiply the allocation rates with the adjusted total material demand coefficients from the material flow model. Thus, we can differentiate between the impacts of waste and provisional reject $b^{\alpha}_{m,j}$ and $b^{\beta+\tau}_{m,j}$ as well as reworking and recycling $b^{\tau}_{m,j}$ and $b^{\lambda}_{m,j}$ on the material demand of a product unit. If we sum up these four components with the efficient total material demand coefficient, we receive the adjusted total material demand coefficient $b_{m,j}$ that we already know from (37):

7 Symbol k represents an additional product and quantity center index with k = 1,…,J.

$$
\begin{aligned}
b_{m,j} &= b'_{m,j} + \sum_{s=1}^{J} ar_{m,s}^{\alpha} \cdot b_{s,j} + \sum_{s=1}^{J} ar_{m,s}^{\beta+\tau} \cdot b_{s,j} - \sum_{s=1}^{J} ar_{m,s}^{\tau} \cdot b_{s,j} - \sum_{s=1}^{J} ar_{m,s}^{\lambda} \cdot b_{s,j} \\
&= \underbrace{b'_{m,j}}_{\substack{\text{efficient}\\ \text{material demand}}} + \underbrace{b_{m,j}^{\alpha}}_{\substack{\text{provisional waste-related}\\ \text{material demand}}} + \underbrace{\underbrace{b_{m,j}^{\beta+\tau}}_{\substack{\text{provisional reject-related}\\ \text{material demand}}} - \underbrace{b_{m,j}^{\tau}}_{\substack{\text{reworking-related}\\ \text{material savings}}}}_{\substack{\text{final reject-related}\\ \text{material demand}}} - \underbrace{b_{m,j}^{\lambda}}_{\substack{\text{recycling-related}\\ \text{material savings}}}
\end{aligned} \tag{50}
$$

In the second chapter, we analyzed the material flows at the level of the company, quantity centers, and product units. Based on this material flow model, we can now develop an MFCA system.

3.3 Development of the material flow cost accounting system

3.3.1 Assumptions and structure of the material flow cost accounting system

MFCA system should provide sustainability management with differentiated information on the costs of products and the cost of material and product losses. For this purpose, we make the following basic assumptions in our MFCA system:

- *Cost type, cost or quantity center, and cost unit accounting*

The common cost accounting systems consist of a cost type, cost center, and cost unit accounting. We assume the same structure for the MFCA system to facilitate its integration into other cost accounting systems and the organization of companies. Regarding the relationship between cost centers and quantity centers, cost centers usually include more than one quantity center (Dierkes and Siepelmeyer, 2019; Günther et al., 2017; ISO, 2011).

- *Full cost accounting system*

MFCA is primarily described as a full cost accounting system (e.g. Chompu-inwai et al., 2015; Dekamin and Barmaki, 2018; May and Günther, 2020). Therefore, we also design a full cost accounting system and do not differentiate between variable and fixed costs.[8]

[8] For MFCA as a marginal cost accounting system, see Dierkes and Siepelmeyer (2019).

- *Determination of the costs of the products as well as material and product losses*

MFCA focuses on determining the costs of the products as well as the costs of the material and product losses (Schmidt and Nakajima, 2013; Schmidt, 2015; Schrack, 2016). To provide the management with differentiated information on a company's environmental impacts and environmental protection measures, we distinguish between the costs of the product-, waste-, reject-, reworking-, recycling-, and disposal-related material flows at the quantity center and product unit level.

- *Cost planning at the quantity center level*

We plan the costs of each cost type at the quantity center level, although cost budgeting has hardly been discussed in MFCA. For cost planning, we can resort to the procedures known from other cost accounting systems (Bhimani et al., 2019; Coenenberg et al., 2016; Datar and Rajan, 2018; Ewert and Wagenhofer, 2014). If cost budgeting is not possible at the quantity center level for technical or economic reasons, it should be done at the cost center level. In this case, the cost center costs must be subdivided among the quantity centers based on suitable allocation criteria.

- *Aggregation of the cost types into cost categories*

The different cost types of a quantity center, such as material costs, wages, depreciation, and other costs, are aggregated into four cost categories: material, energy, system, and waste management costs (Bux and Amicarelli, 2022; ISO, 2011, Kawalla et al., 2018). All primary material and energy cost types are allocated to the material and energy costs. The other remaining cost types are assigned according to their particular use in the transformation processes to system and waste management costs. The waste management costs consist only of the costs directly related to the treatment, transportation, and reduction of the material and product losses, whereas system costs cannot be clearly attributed to the material and product losses (May and Günther, 2020; Nishimura et al., 2021; Schmidt, 2005).

- *Application of the material distribution key*

The material distribution key is used in MFCA to subdivide the energy and system costs on the basis of the material quantities between the products and the material and product losses (Behnami et al., 2019; Günther et al., 2017; Schmidt and Nakajima, 2013). Accordingly, we use this allocation criterion in our more differentiated MFCA system for each allocation of costs to material flows and thus also, for example, to allocate waste management costs to different material flows.

- *Allocation of the efficient costs between the manufacturing quantity centers*

In our material flow model, we do not allocate the materials between the quantity centers relating to the material and product losses. Accordingly, we assign only the costs of the products among the manufacturing quantity centers (Günther et al., 2015; Ho et al., 2021; ISO, 2011). The costs of the provisional waste and the final reject as well as the ones for recycling and disposal are assigned from the quantity centers to the product units.

Based on the assumptions, we obtain the structure of the MFCA system illustrated in Figure 8.

cost type accounting

- appropriate structure of the primary cost types

cost and quantity center accounting

- disassembling of the cost centers into manufacturing, recycling, and disposal quantity centers
- identification of the cost drivers and planning of the costs per cost type
- assignment of the costs to material, energy, system, and waste management costs
- allocation of the material costs to the products and the material and product losses based on the material flow model
- assignment of the energy, system, and waste management costs to the products as well as material and product losses with the material distribution key
- allocation of the efficient costs between the manufacturing quantity centers
- determining separate cost rates for the costs of the products as well as material and product losses

cost unit accounting

- calculation of the product unit costs differentiated by the costs of the products and the costs of the material and product losses

Figure 8: Structure of the material flow cost accounting system

After the discussion of the central assumptions and structure of the MFCA system, we explain the single cost budgeting steps in the next chapter.

3.3.2 Quantity center accounting

The costs of a ***manufacturing quantity center*** are divided into the costs of the four cost categories material cost, energy costs, system costs, and waste management costs, which can be further subdivided into primary and secondary costs (Dierkes and Siepelmeyer, 2019). Using the material flow model and the material distribution key, these costs can be allocated to products as well as to the material and product losses. The product costs can be separated into the costs of provisional production yield and reworked products. Accordingly, the costs of the material and product losses can be divided into the cost of final rejects and costs of provisional waste. Furthermore, we can split the costs of provisional waste into the costs of provisional material and intermediate product waste, with the material costs including only the primary costs and secondary costs, respectively. Additionally, we must consider the costs for the reworking-related material demand (Keilus, 1993; Letmathe, 1998), which we did not include in the material flow model. The waste management costs consist only of primary costs because no inefficient costs are allocated between the manufacturing quantity centers. The primary energy, system, and waste management costs are assigned with the material distribution key (MDK) to the material flows (Ho et al., 2021; ISO, 2011; Kawalla et al., 2018). The cost planning in a manufacturing quantity center can be summarized in a cost calculation scheme, as illustrated in Table 6. For allocating the costs to the product units, we use the allocation bases according to the material flow model in chapter 3.2.5. Therefore, the costs of the provisional production yield are allocated based on the faultlessly manufactured products $rp_j - rv_j$. In contrast, the manufacturing costs of the other elements are distributed based on the production volume rp_j.

	Cost categories	Product			Material and product losses					Sum
		Provisional production yield	Reworked product	Sum	Reworking-related materials	Final rejects	Provisional waste		Sum	
							Materials	Products		
	Material costs (1)									
	Primary costs									
+	*Secondary costs*									
=	*Sum*									
	Energy costs (2)								*MDK*	
	Primary costs									*Plan*
+	*Secondary costs*									
=	*Sum*									
	System costs (3)								*MDK*	
	Primary costs									*Plan*
+	*Secondary costs*									
=	*Sum*									
	Waste management costs (4)								*MDK*	
	Primary costs									*Plan*
+	*Secondary costs*									
=	*Sum*									
	Manufacturing costs (1)+(2)+(3)+(4)									
	Primary costs									
+	*Secondary costs*									
=	*Sum*									
	Cost allocation base	$rp_j - rv_j$	rp_j		rp_j	rp_j	rp_j	rp_j		
	Cost rate									

Table 10: Cost calculation scheme of a manufacturing quantity center

The costs of the ***product recycling quantity centers*** are structured into the costs of their outgoing material flows and the four cost categories. The material costs can be divided into primary and secondary costs, whereas energy, system, and waste management costs include only primary costs, because we do not allocate inefficient costs other than material costs from the manufacturing quantity centers to the recycling quantity centers. The costs of the product recycling quantity centers are subdivided among the recycled products and materials as well as the recycling-related materials and the material and product losses. We separate the costs of the recycling-related materials from the costs of recycled products and materials to determine the opposing economic effects of the recycling measures at the quantity center and product unit level, as it is common in environmental cost accounting (Diaz et al., 2022; Keilus, 1993, Letmathe, 1998). The costs of the material flows are allocated based on the production quantities of the manufacturing quantity centers to the product units according to the material flow model in chapter 3.2.5. The result of the cost planning in a product recycling quantity center is summarized in Table 11.

Cost categories		***Recycled***		**Losses**				***Sum***
		Products	*Materials*	*Recycling-related materials*	*Products*	*Materials*	*Sum*	
Material costs (1)								
	Primary costs							
+	Secondary costs							
=	Sum							
Energy costs (2)							MDK	
	Primary costs							*Plan*
System costs (3)							MDK	
	Primary costs							*Plan*
Waste management costs (4)							MDK	
	Primary costs							*Plan*
Recycling costs (1)+(2)+(3)+(4)								
	Primary costs							
+	Secondary costs							
=	Sum							
Cost allocation base		rp_j	rp_j	rp_j	rp_j	rp_j		
Cost rate								

Table 11: Cost calculation scheme of a product recycling quantity center

Since the cost calculation schemes of the material recycling quantity centers and those of the product and material disposing quantity centers are structured accordingly, we will not go into more detail here. As a result, we have all the necessary cost rates of the quantity centers for cost unit accounting.

3.3.3 Cost unit accounting

In cost unit accounting, we calculate the product unit costs consisting of the efficient, inefficient, and inefficiency decreasing costs of the manufacturing, recycling, and disposal quantity centers. We develop a flexible designed product unit cost calculation scheme to allocate waste, rejects, reworking, and recycling costs for single- and multi-dimensional analyses to provide sustainability management with decision-useful cost information.

To determine the product unit costs, we need to allocate the costs of the different material flows from all manufacturing, recycling, and disposal quantity centers to the product units involved in producing a product (Dierkes and Siepelmeyer, 2019). We have to multiply the cost rate of each material flow of these quantity centers with the corresponding adjusted total material demand coefficient and sum up the cost amounts over all material flows, cost categories, and quantity centers. Thus, we obtain the manufacturing, recycling, and disposal costs per product unit, which add up to the product unit costs. Each of the three elements can be further subdivided. The manufacturing quantity center costs per product unit can be split into the efficient, waste-, reject-, and reworking-related manufacturing costs as well as the reworking-related manufacturing costs saving per product unit. The recycling costs per product unit can be disaggregated into the recycling-related material cost savings per product unit, the recycling-related material costs increase per product unit, and the loss-related costs per product unit. To calculate these costs, we assign the costs of the material flows from all product and material recycling quantity centers to the product unit. To determine the disposal costs per product unit, we allocate the disposal costs of the material and product losses in the disposal quantity centers caused by a product unit. Since the disposal quantity centers include only one material or product, we forego further separation in the following calculation scheme of the product unit costs.

+	Efficient manufacturing costs per product unit
+	Waste-related manufacturing costs per product unit
+	Reject-related manufacturing costs per product unit
–	Reworking-related manufacturing cost savings per product unit
+	Reworking-related manufacturing cost increase per product unit
=	***Manufacturing costs per product unit (1)***
–	Recycling-related material cost savings per product unit
+	Recycling-related cost increase per product unit
+	Loss-related costs per product unit
=	***Recycling costs per product unit (2)***
	Disposal costs per product unit (3)
=	***Product unit costs (1)+(2)+(3)***

Table 12: Cost calculation scheme of the product unit costs

Furthermore, the product unit costs can be disaggregated according to other analysis criteria, such as cost categories, quantity centers, primary and secondary costs, efficient, inefficient, and inefficiency-decreasing costs, materials and products, and material types. This variety of analysis dimensions allows for adjusting product unit costs to the information needs of sustainability management. In additional multi-dimensional analyses, we can combine the analysis dimensions, for example, the criteria cost categories and quantity centers, which provide insights into the cost structure of the quantity centers and their cost contributions to the product unit costs (Bhimani et al., 2019; Coenenberg et al., 2016; Datar and Rajan, 2018). Moreover, changing the sequence of the analysis criteria can provide additional insights into the product unit costs.

3.3.4 Effects and alternatives to the use of the material distribution key

The material distribution key is used in MFCA to distribute the energy and system costs between the products and the material losses (Bux and Amicarelli, 2022; Ho et al., 2021; Kawalla et al., 2018). Accordingly, products are charged with higher costs the higher their material demand, which can be interpreted as penalty costs for material consumption. Consequently, quantity center owners or product managers are incentivized to reduce the material demand of the product, especially the material and product losses. This is sensible from a sustainability perspective, as efforts in a company are mainly directed at reducing the material demand, but this procedure does not sufficiently take into account the cost drivers of system, energy, and waste management costs (ISO, 2011; Wagner, 2015).

If MFCA is used to provide decision-useful information, the material distribution key often leads to an unjustified cost burden of the material and product losses. In addition, the use of material distribution key results in problems in the integration of MFCA into other cost accounting systems, since they usually allocate the costs according to the principle of cost causation or cost demand (Coenenberg et al., 2016; Datar and Rajan, 2018; Kilger et al., 2012). To provide decision-useful information and to increase the connectivity of MFCA with more established cost accounting systems, we should use allocation criteria, such as production quantities, manufacturing minutes or number of processes to allocate costs to the products and the material and product losses. Compared to the material distribution key, these allocation criteria are more related to the production processes of a quantity center (Bhimani et al., 2019; Guan et al., 2009; Kilger et al., 2012). Moreover, the focus on the corporate transformation processes lead to the idea of an activity-based expansion of MFCA. In this case, the costs in quantity centers are allocated based on the activities among the products as well as the material and product losses, as it is known from activity-based costing (Cooper and Kaplan, 1988; Jing and Songqing, 2011; Schweitzer et al., 2016). This results in even more precise cost allocation, but one must weigh the related benefits against the additional information costs.

3.4 Conclusion

Sustainability management need consistent cost information about the transformation processes in a company. One suitable cost accounting system for this purpose is MFCA because it separately determines the costs of the products and those of the materials and product losses (Kitada et al., 2022; Nishitani et al., 2022; Wagner, 2015). However, MFCA has paid less attention to different drivers of the material and product loss creation and the related costs. Accordingly, the economic and environmental consequences of environmental impacts, such as waste and reject as well as environmental protection measures, such as reworking and recycling, remain unclear.

Therefore, we developed an MFCA system for budgeting the costs of the products as well as the costs of the material and product losses. We designed a production theory-based material flow model that considers the effects of waste, rejects, reworking, and recycling on the material demand of a company for complex transformation processes. Moreover, we analyzed the material flows of a company's manufacturing, recycling, and disposal quantity centers and allocated the material demands, differentiated by the material increasing and reducing effects, from the quantity centers to the product units. Based on the material flow model, we presented the assumptions and structure of an MFCA as a full cost accounting system. Its main characteristic is the possibility to analyze the effects of waste, rejects, reworking, and recycling on the costs of products and the costs of materials and product losses at the company, quantity center, and product unit levels. MFCA provides sustainability management with relevant cost information, but you have to keep in mind the consequences of using the material distribution key, which results in cost charges according to the material demand. Although this leads to a desirable incentive to reduce material losses from a sustainability perspective, this does not necessarily correspond to cost causation. For this reason, we concluded by discussing alternative cost allocations that result in a more precise cost allocation.

The developed MFCA system can be expanded in many ways. Further inefficiency factors, such as throughput speed, human error, or material quality, can be integrated into the material flow model (Dierkes and Siepelmeyer, 2019; Kilger et al., 2012; Schmidt, 2015). Furthermore, the cost accounting system can be expanded from a single company to the entire value chain of a product and thereby helps to measure the product- and material loss-related costs at each value added stage (Günther et al., 2015; Schmidt et al., 2015; Schrack, 2016). Finally, the external costs of the production activities can be included into the MFCA system to provide sustainability management information on the costs of all environmental impacts of a company's products as well as material and product losses.

4. Development and Application of the Discounted Value Added Approach in Sustainability Management

Stefan Dierkes and David Siepelmeyer

Abstract

In this paper, we develop the discounted value added approach to provide sustainability management information on the impacts of decisions on future value added creation and distribution. We use value added statements from sustainability reporting to forecast a company's value added-related payments. Combining the future-oriented value added statements with a discounted cash flow approach, we determine the market value of the future value added and its distribution among the workers, community, equity holders, and debt holders. We also show how to analyze market values regarding their economic and social impacts in one-dimensional and multi-dimensional analyses. Finally, we calculate value added- and stakeholder-related key ratios supporting sustainability management in short- and long-term decision-making.

Keywords

Value added statement, Stakeholder-oriented management, Corporate social responsibility, Stakeholder value

JEL-Classification

Q56

4.1 Introduction

Value-based management focuses on the financial success of the equity holders, while the interests of the other stakeholders are only considered as long as they contribute to the financial success of the equity holders. Due to this shareholder orientation, discounted cash flow approaches have become central tools for long-term corporate decision-making in value-based management (Berk and DeMarzo, 2020, p. 685; Koller et al. 2020, p. 137-163). However, in recent years, the emphasis has shifted to other stakeholders, such as customers, workers, and the community, with the increasing relevance of social and environmental issues. Therefore, sustainability management has to align the business activities with their impacts along the entire value chain on the economic, environmental, and social goals of the stakeholder of a company (Freeman et al. 2004; Müller et al. 2013; Müller-Christ, 2020, p. 297). As a result, companies increasingly have to inform the stakeholders and the public about these consequences in separate sustainability reports (Global Reporting Initiative [GRI], 2020; Sustainability Accounting Standard Board [SASB], 2017). Value added statements are an element of sustainability reports, which inform about the creation and distribution of corporate successes from the perspective of multiple stakeholders in past periods. In contrast to the use of value added statements in sustainability reporting, they have hardly been used in sustainability management. In this respect, it is unclear how to forecast value added statements and reconcile them with balance sheets and income statements. Moreover, to compare business strategies regarding their impacts on the creation and distribution of value added in a multi-period setting, we have to determine their present value. This led to the idea of combining value added statements with discounted cash flow approaches, which requires the determination of value added on cash flows and not, as is common in sustainability reporting, on revenues and expenses.

For this reason, we develop on the basis of internal forecast calculations cash flow-based value added statements to determine the created and distributed value added. We integrate the future-oriented value added statements into the discounted cash flow approaches to calculate the market value of the future value added and the market values of the stakeholders' future successes. Furthermore, we analyze the market values regarding their economic and social impacts and even provide some environmental information. Finally, we discuss the use of one-dimensional and multi-dimensional analyses with absolute and relative value added- and stakeholder-related key ratios in sustainability management.

Value added statements were initially developed and used by economists in many European countries to measure a country's annual gross domestic product and its distribution to companies, households, and the state for national income (Haller et al. 2018, p. 765; Haller, 1997, p. 77-83). Since the beginning of the 20th century, this instrument has been adopted on a corporate level to determine the created value added and disclose its distribution among a company's main stakeholders (Haller and Stolowy, 1998; Lehmann, 1954; Nicklisch, 1932). Due to the stakeholder-oriented definition of the corporate success, value added statements have been used in corporate reporting to provide the public with comprehensive information on the impacts of a company. But despite their usefulness, the public interest in value added statements decreased at the end of the 1980s (Burchell et al. 1985, p. 405; Morley, 1979, p. 618; Van Staden, 2004, p. 3). This development can be partly explained by a narrowing focus on the financial success of the equity holders at that time and the beginning of value-based management that dominated corporate practices in the subsequent decades. However, sustainability reporting now offers a new application for value added statements (Arangies et al. 2008; Bagieńska, 2017; Haller and van Staden, 2014; Zéghal and Maaloul, 2010).

In sustainability reporting, comparatively little attention has been paid to the structure and use of value added statements, although critical aspects of value added statements are included in international accounting frameworks (GRI, 2020; SASB, 2017). Still, in North American, European, Asian, and African countries, companies currently have no legal obligation to publish value added statements. Consequently, only a few companies voluntarily publish these statements in their sustainability reports. And in the case of publication, value added statements are not published regularly, and the value added mostly consists only of the sum of the personnel expenditures, corporate taxes, interests, and profits (BMW Group, 2021, p. 138; Deutsche Börse, 2021, p. 50; EnBW, 2020, p. 34; Fraport, 2021, p. 113). But this is already known from the companies' income statements, so stakeholders do not obtain new information on value creation and distribution. However, value added statements could provide additional information if they include other components of the stakeholders' successes, such as further education costs, voluntary social grants, or donations.

To get ideas for possible extensions of value added statements, we can use social balance sheets. In social balance sheets, a company's positive and negative social and environmental impacts are monetized and offset against each other. They include various social and environmental elements, such as investments in a company cafeteria, safety costs, and environmental protection costs (Berthoin Antal and Sobczak, 2005; Berthoin Antal et al. 2009; Dierkes et al. 2002). In this respect, social balance sheets offer essential elements for extending value added statements, but they have not yet been integrated into value added statements in practice. In contrast, companies pay more attention to economic, environmental, and social key ratios in their sustainability reporting to inform about their sustainability performance. But the definition and determination of key ratios differ even among companies in the same industry, which restricts the information content of sustainability reports (Hossain et al. 2021; Koç and Durmaz, 2015). Hence, it is understandable that research in sustainability reporting currently focuses mainly on standardizing companies' sustainability reports to increase their comparability (Cöster et al., 2020; Hamilton and Waters, 2022; Machado et al., 2021; Steinhöfel et al., 2019). Accordingly, the standardization of value added statements might also boost their application in sustainability reporting, but this is not our focus because we want to use value added statements in sustainability management for corporate decision-making and behavioral control.

For the measurement of the value added and the determination of the success of an interest group, different approaches already exist in value-based management. Strack et al. (2009), Strack and Villis (2001), and Fischer and Vielmeyer (2002) measure the periodic contributions of different stakeholders to the future success of the equity and debt holders with planned stakeholder-related key ratios, such as value added per customer and the average costs per customer as well as value added per person and the average cost per person. The determination of the stakeholder-related key ratios starts with decomposing the economic value added or cash value added into the revenues and expense items. The stakeholder-specific expenses are separated from other expenses, and the latter are aggregated with the revenues to obtain a value added. Afterward, two stakeholder-specific key ratios can be determined by dividing the two components by a stakeholder-specific quantity, such as the number of customers or employees. While these key ratios highlight the relevance of the different stakeholders for the success of the capital holders, they lack of a theoretical sound embedment into value added statements with the creation and distribution of value added as the success of different stakeholders. Furthermore, the focus of the key ratios is still on the economic value added and cash value added as shareholder-oriented figures limiting their potential usefulness for sustainability management.

Fitz-Enz (2009) and Scholz et al. (2011) determine the created success per employee in a period in their human capital value added approach. They divide a company's value added by the total quantity of the workers' full working time equivalent. The value added is determined by subtracting all expenses from a company's sales and changes in inventory unrelated to the employees. The value added is denoted as the worker's success, although it also includes the profits of shareholders and other stakeholders. Therefore, Fitz-Enz (2009) and Scholz et al. (2011) do not distinguish between the creation and distribution of the value added, restricting differentiated analysis of the stakeholders' successes. Hence, this approach also lacks of a clear reference to value added statements.

Dierkes et al. (2016) develop cash flow-based value added statements to determine the future success of a company's stakeholders. In their value added statement model, they determine the future corporate success from the perspective of the workers, state, equity holders, and debt holders. However, employee-related payments and net investments, as well as corporate taxes, are the only elements of the worker's and state's success. Additional success components, such as education costs or investments for society, are discussed only as theoretical expansions of their value added statement model. Accordingly, critical elements of the created and distributed value added are unclear. Moreover, although Dierkes et al. (2016) propose to determine the market values of the future value added, they do not specify the discount rates required for valuation.

To overcome the previously described theoretical and practical shortcomings, we develop the discounted value added approach. We forecast a company's value added-related payments with a value driver model, which is common in value-based management. On this basis, we conceive future-oriented value added statements on cash flows that are used to calculate the value added creation and distribution for an infinite time horizon. We discount the future value added by the appropriate cost of capital to determine the market value of the future value added that we denote as stakeholder value. Furthermore, we analyze stakeholder value creation and its distribution among the workers, community, equity holders, and debt holders. In contrast to sustainability reporting, we use an expanded value added statement model; hence, the discounted value added approach provides detailed information on the impacts of the decisions in sustainability management. We examine the stakeholder value and the market values of the stakeholders' successes with one-dimensional and multi-dimensional analyses regarding their economic and social effects, while also providing some environmental information. Finally, we develop different value added- and stakeholder-related key ratios that can assist sustainability management in corporate decision-making and behavioral control.

This paper proceeds as follows. In the second chapter, we develop future-oriented value added statements and show the basic conception of the discounted value added approach. In the third chapter, we analyze in detail the creation and distribution of the stakeholder value regarding their economic and social impacts. In the last chapter, we summarize the main results and give an outlook of subsequent research in the field of value added statements.

4.2 Basic conception of the discounted value added approach

4.2.1 Future-oriented value added statements

Value added is a surplus figure representing the corporate success from the perspective of multiple stakeholders (Haller et al. 2018, p. 765). Its periodical creation is measured in the creation calculation of a value added statement, whereas its allocation among the stakeholders is analyzed in the distribution calculation. The level of value added depends on the number of stakeholders considered. A stakeholder group is an accumulation of individuals who pursue common goals with their participation in a company or are jointly affected by the impacts of a company's business activities. The stakeholders are usually subdivided into primary and secondary ones (Freeman et al. 2004; Freeman et al. 2007). Primary stakeholders are directly involved in a company's business processes, such as equity holders, debt holders, workers, customers, suppliers, or the state. In contrast, secondary stakeholders have no direct connection to a company's business activities, such as residents, the public, or non-governmental organizations (NGOs). Owing to their legal position and their relevance to the management of a company, the focus in sustainability reporting is on the success of the equity holders, debt holders, workers, and community (BMW Group, 2021, p. 138; Deutsche Börse, 2021, p. 50; Fraport, 2021, p. 113; Haller et al. 2018; Haller, 1997). Therefore, we also determine the future value added from the perspective of these four stakeholders. Nevertheless, depending on the purpose, value added statements can be flexible designed in terms of the number of stakeholders included.

To use value added statements for the management of a company, the focus needs to be turned from the analysis of the past to the prediction of the future value added. The forecast of the value added for a multi-periodic time horizon requires the development of cash flow-based value added statements, which additionally enables the determination of the present value of the future created and distributed value added (Dierkes et al. 2016). The starting point for planning future value added are the already existing internal forecast calculations from value-based management. In these calculations, the cash flows of a company's investing, operating, and financing activities are forecasted for each future period using an appropriate value driver model, and they are reconciled with planned balance sheets and income statements.[9] As a result of the internal forecast calculations, we can determine the future free cash flow $E[\widetilde{FCF}_t]$ by subtracting the corporate taxes of the unlevered firm $E[\tilde{T}_t^u]$ and the corporate investments $E[\widetilde{Inv}_t]$ from the earnings before interest, taxes, depreciation, and amortization $E[\widetilde{EBITDA}_t]$ (Ballwieser and Hachmeister, 2021, p. 13-16; Koller et al. 2020, p. 161-163):[10]

$$E[\widetilde{FCF}_t] = E[\widetilde{EBITDA}_t] - E[\tilde{T}_t^u] - E[\widetilde{Inv}_t] \tag{51}$$

To consider the value effects of a company's financing activities, we have to take into account the debt levels. Here, the financing policy of a company plays an important role, whereby active or passive debt management are the most prominent financing strategies (Koller et al. 2020, p. 161; Kruschwitz and Löffler, 2006, p. 68).[11] We assume active debt management with a constant debt ratio. Therefore, the firm values can be calculated with the free cash flow approach without circularity problems, so that the debt ratio and firm values can be used to calculate the debt level for each future period. The tax deductibility of the interest payments leads to tax savings, denoted as tax shield $E[\widetilde{TS}_t]$. If we add the tax shield to the free cash flow according to (51), we obtain the total cash flow $E[\widetilde{TCF}_t]$ with $E[\tilde{T}_t^{\ell}]$ as the taxes of a levered firm (Ballwieser and Hachmeister, 2021, p. 195):

9 For an overview of the existing value driver models, see Berk and DeMarzo (2020, p. 729-737), Koller et al. (2020, p. 229-251), Penman (2022, p. 480-492), and Rappaport (1998, p. 68).

10 $E[\cdot]$ is used as an expectation operator, t represents the time index, and a tilde indicates a variable's future uncertainty.

11 Active debt management is characterized by determining the future debt ratios at the valuation date, whereas in passive debt management, the debt market value is planned for each future period.

$$
\begin{aligned}
E[\widetilde{TCF}_t] &= E[\widetilde{FCF}_t] + E[\widetilde{TS}_t] \\
&= E[\widetilde{EBITDA}_t] - E[\widetilde{T}_t^{\ell}] - E[\widetilde{Inv}_t]
\end{aligned}
\tag{52}
$$

The total cash flow represents the future corporate success from the perspective of the equity and debt holders that can be subdivided into the flow to equity $E[\widetilde{FtE}_t]$ and debt $E[\widetilde{FtD}_t]$ (Diedrich and Dierkes, 2015, p. 35):

$$
E[\widetilde{EBITDA}_t] - E[\widetilde{T}_t^{\ell}] - E[\widetilde{Inv}_t] = E[\widetilde{FtE}_t] + E[\widetilde{FtD}_t] \tag{53}
$$

To determine the success of the workers and the community, we need to identify all components of the total cash flow in (52) that represent a success for these two interest groups. The success of the workers consists of employee-related payments $E[\widetilde{W}_t]$ and employee-related investments $E[\widetilde{Inv}_t^{w}]$. The employee-related payments include, for instance, wages, further education costs, and health insurance contributions, whereas the employee-related investments consist of investments into a company kindergarten, cafeteria, or apartments (Aldama and Zicari, 2012, p. 490; Dierkes et al. 2002, p. 6; Kuasirikun and Sherer, 2004, p. 638).

The community's success consists of the community-related payments $E[\widetilde{C}_t]$, the community-related investments $E[\widetilde{Inv}_t^{c}]$ as well as the taxes of the levered firm. Community-related payments include, for example, donations, fees, or customs duty. The community-related investments contain corporate investments into company buildings that are provided free of charge to the community, such as youth workshops or seminar rooms (Dierkes et al. 2002, p. 6; Kuasirikun and Sherer, 2004, p. 638). The delimitation of the community-related investments from the corporate investments is done in the same way as the employee-related ones. Afterwards, all other remaining payment types from (52) that do not belong to the success of one of the four interest groups are summarized to the adjusted earnings before interest, taxes, depreciation, and amortization $E[\widetilde{EBITDA}_t^{*}]$ and the adjusted corporate investments $E[\widetilde{Inv}_t^{*}]$. Thus, the total cash flow in (53) can be rewritten as follows:

$$E[\widetilde{EBITDA}_t^*]-E[\tilde{T}_t^\ell]-E[\tilde{C}_t]-E[\tilde{W}_t]-E[\widetilde{Inv}_t^c]-E[\widetilde{Inv}_t^w]-E[\widetilde{Inv}_t^*]=E[\widetilde{FtE}_t]+E[\widetilde{FtD}_t] \quad (54)$$

Finally, solving (54) for all components of the success of the workers, community, equity holders, and debt holders, we obtain the future value added on cash flows $E[\widetilde{VA}_t]$ (Dierkes et al. 2016, p. 245):

$$\begin{aligned} E[\widetilde{VA}_t] &= \underbrace{E[\widetilde{EBITDA}_t^*]-E[\widetilde{Inv}_t^*]}_{\text{creation calculation}} \\ &= \underbrace{E[\tilde{W}_t]+E[\widetilde{Inv}_t^w]}_{\text{workers}}+\underbrace{E[\tilde{T}_t^\ell]+E[\tilde{C}_t]+E[\widetilde{Inv}_t^c]}_{\text{community}}+\underbrace{E[\widetilde{FtE}_t]}_{\text{equity holders}}+\underbrace{E[\widetilde{FtD}_t]}_{\text{debt holders}} \\ &= \underbrace{\underbrace{E[\widetilde{FtW}_t]}_{\text{workers}}+\underbrace{E[\widetilde{FtC}_t]}_{\text{community}}+\underbrace{E[\widetilde{FtE}_t]}_{\text{equity holders}}+\underbrace{E[\widetilde{FtD}_t]}_{\text{debt holders}}}_{\text{distribution calculation}} \end{aligned} \quad (55)$$

From the creation calculation in (55), sustainability management obtains information on the level of the future created value added, while the distribution calculation informs about the future successes of the four interest groups. According to the flow to equity and flow to debt, we denote the payments of the workers and the community as flow to worker $E[\widetilde{FtW}_t]$ and flow to community $E[\widetilde{FtC}_t]$, respectively.

4.2.2 Discounted Value Added Approach

The impact of the decisions of sustainability management on the future value added creation and distribution mostly extends not over one but several periods. Therefore, we have to analyze all periods in which the value added creation and distribution are affected by a management decision. In value-based management, the impacts on the financial goals of the equity and debt holders are usually analyzed for all future periods by calculating the market value of a company (Hillier et al. 2020; Koller et al. 2020). Therefore, it is appropriate to determine the market value of the future value added to analyze the short- and long-term impacts for the workers, community, equity holders, and debt holders. For this reason, we forecast the value added creation and distribution for all future periods on the basis of internal forecast calculations, whereby we subdivide the infinite forecast horizon into an explicit forecast period and a steady-state, as it is common in value-based management (Berk and DeMarzo, 2020; Koller et al. 2020; Rappaport, 1998).

In the explicit forecast period running from $t=1$ to T, the future cash flows are planned in detail on the base of the developed future-oriented value added statements. In comparison to the value driver model in value-based management, we need a more complex value driver model, because we have to determine the created value added with its distribution to the four stakeholders. Additionally, the more we disaggregate the value added into single components, the value driver model gets even more complex. However, using a more complex value driver model incurs higher information costs, which have to be weighed against the additional information benefits.

For forecasting the value added in the steady-state, starting with period $T+1$, we assume, as it is common in corporate valuation, that all elements of the cash flow grow at the nominal growth rate g, that is driven by the profitability of a company, the industry development, and the long-term inflation rate (Drukarczyk and Schüler, 2021, p. 140; Koller et al. 2020, p. 213-230; Penman, 2022, p. 154). Therefore, the proportions of the cash flow elements in the steady-state remain constant. Accordingly, we assume that the value added and the success of the four stakeholders with their elements also increase by the same nominal growth rate, which leads to constant proportions of the stakeholders on the distributed value added.

Based on the internal forecast calculations, the future-oriented value added statements and the nominal growth rate, we forecast the value added creation and its distribution among the workers, community, equity holders, and debt holders for the explicit forecast period and the steady-state, which is illustrated in Table 13.

Period		Explicit Forecast Period			Steady-state
		1	…	T	T+1
		creation calculation			
	Value added				
		distribution calculation			
	Flow to worker				
+	Flow to community				
+	Flow to equity				
+	Flow to debt				
=	Value added				

Table 13: Forecast of the future value added creation and distribution

The business strategies of sustainability management differ regarding the level, timing, and distribution of the value added. To compare their short- and long-term impacts, we need to know the present value of the future value added. In value-based management, the market value of a cash flow represents the present value of a business strategy that is usually determined with the discounted cash flow approaches. However, these valuation tools focus on the determination of the equity and debt market values, whereas the ones of the workers and the community are unclear. To determine the market values of the flow to worker and flow to community, we combine the future-oriented value added statements with a discounted cash flow approach, which ensures a capital market-oriented valuation of the future value added creation and distribution. This approach could be accused of using capital market-based valuation criteria incompatible with a stakeholder-specific valuation. However, its advantage is that the valuation approach can be directly integrated into the determination of the market value of a company in value-based management, which ensures the connectivity of this stakeholder-oriented valuation tool to other valuation approaches that are widely accepted in theory and practice. But for the use of this tool in sustainability management one has to keep in mind, that the market values of the flow to worker and the flow to community are not determined from the perspective of these stakeholders, but from the valuation criteria of the capital market.

The flow to equity is already known from (53). Thus, we can directly determine the equity market value E^{ℓ} by discounting the expected flows to equity by the cost of equity ke^{ℓ} that is determined on the financial capital market with the capital asset pricing model (Ballwieser and Hachmeister, 2021, p. 192; Berk and DeMarzo, 2020, p. 679):[12]

[12] We assume a constant debt ratio and thus constant costs of equity and debt for all future periods.

$$E^{\ell} = \underbrace{\sum_{t=1}^{T} \frac{E[\widetilde{FtE}_t]}{(1+ke^{\ell})^t}}_{\text{explicit forecast period}} + \underbrace{\frac{E[\widetilde{FtE}_{T+1}]}{(1+ke^{\ell})^T \cdot (ke^{\ell} - g)}}_{\text{steady state}} \tag{56}$$

According to (56), the debt market value can be determined by discounting the expected flows to debt by the cost of debt kd that consists of a risk-free interest rate and a company-specific credit spread (Hillier et al. 2020, p. 325; Koller et al. 2020, p. 284; Penman, 2022, p. 446-450):

$$D = \underbrace{\sum_{t=1}^{T} \frac{E[\widetilde{FtD}_t]}{(1+kd)^t}}_{\text{explicit forecast period}} + \underbrace{\frac{E[\widetilde{FtD}_{T+1}]}{(1+kd)^T \cdot (kd - g)}}_{\text{steady state}} \tag{57}$$

In contrast to (56) and (57), it is unclear which cost of capital can be used to determine the market value of the future value added as well as the market values of the flow to worker and flow to community. Theoretically, it is possible to aggregate payment type-specific costs of capital to stakeholder-specific ones (Berk and DeMarzo, 2020, p. 282; Brealey et al. 2019, p. 224). But these costs of capital are neither observable on the capital market nor on the labor market. Therefore, we determine the market values in a different way. According to the total cash flow approach, the market value of a company V^{ℓ} is determined by discounting the expected total cash flows by the average cost of capital k. This cost of capital consists of the cost of equity and debt weighted by the equity ratio $(1-\Theta)$ and debt ratio Θ (Koller et al. 2020, p. 138-163; Kruschwitz and Löffler, 2006, p. 68):

$$V^{\ell} = \underbrace{\sum_{t=1}^{T} \frac{E[\widetilde{TCF}_t]}{(1+k)^t}}_{\text{explicit forecast period}} + \underbrace{\frac{E[\widetilde{TCF}_{T+1}]}{(1+k)^T \cdot (k - g)}}_{\text{steady state}} \qquad \text{with } k = ke^{\ell} \cdot (1-\Theta) + kd \cdot \Theta \tag{58}$$

The firm value in (58) corresponds to the sum of the equity and debt market values in (56) and (57). To determine the market value of the future value added and the market values of the flow to worker and flow to community, the total cash flow in (54) has to be inserted into (58). If we solve afterward for the market values of the four stakeholders' future successes, we obtain the market value of the future value added VVA that we denote as stakeholder value:

$$
\begin{aligned}
\mathrm{VVA} &= \sum_{t=1}^{T} \frac{E[\widetilde{VA}_t]}{(1+k)^t} + \frac{E[\widetilde{VA}_{T+1}]}{(1+k)^T \cdot (k-g)} && \text{stakeholder value} \\
&= \sum_{t=1}^{T} \frac{E[\widetilde{FtW}_t]}{(1+k)^t} + \frac{E[\widetilde{FtW}_{T+1}]}{(1+k)^T \cdot (k-g)} && \text{market value flow to worker} \\
&\quad + \sum_{t=1}^{T} \frac{E[\widetilde{FtC}_t]}{(1+k)^t} + \frac{E[\widetilde{FtC}_{T+1}]}{(1+k)^T \cdot (k-g)} && \text{market value flow to community} \\
&\quad + \sum_{t=1}^{T} \frac{E[\widetilde{FtE}_t]}{(1+ke^{\ell})^t} + \frac{E[\widetilde{FtE}_{T+1}]}{(1+ke^{\ell})^T \cdot (ke^{\ell}-g)} && \text{equity market value} \\
&\quad + \sum_{t=1}^{T} \frac{E[\widetilde{FtD}_t]}{(1+kd)^t} + \frac{E[\widetilde{FtD}_{T+1}]}{(1+kd)^T \cdot (kd-g)} && \text{debt market value}
\end{aligned}
\tag{59}
$$

Due to the integration of the future-oriented value added statements into the discounted cash flow approaches, we can determine the stakeholder value and the market values of the future successes of the workers, community, equity holders, and debt holders. We denote this valuation tool as the discounted value added approach. It can be used not only for determining the market values at the valuation date, but also for calculating the expected market values for any future period. Therefore, we can also analyze the development of the stakeholder value creation and distribution over time, as illustrated in Table 14.

Period	Explicit forecast period				Steady-state
	0	1	…	T	T+1
creation calculation					
Value added					
Stakeholder value					
distribution calculation					
Workers					
Flow to worker					
Market value flow to worker					
Community					
Flow to community					
Market value flow to community					
equity holders					
Flow to equity					
Equity market value					
debt holders					
Flow to debt					
Debt market value					

Table 14: Structure of the discounted value added approach

In this chapter, the stakeholder value creation and distribution have been determined on an aggregated level. In the following chapter, we describe in detail the use of the discounted value added approach in sustainability management.

4.3 Further development and use of the discounted value added approach

4.3.1 Application of the discounted value added approach in sustainability management

The discounted value added approach can be used in sustainability management to analyze the effects of short- and long-term decisions on the stakeholder value and the market values of the success of the workers, community, equity holders, and debt holders. The approach is based on forecasted cash flow-based value added statements for an infinite time horizon. The short-term impacts are determined with cash flow-based value added statements for each future period, whereby the value added statements can also be calculated on revenues and expenses as well as on benefits and costs (Coenenberg et al. 2021, p. 1253; Haller, 1997, p. 105-152; Weber, 1980, p. 5). To measure the long-term impacts, sustainability management should use cash flow-based value added statements to determine the stakeholder value with its distribution to stakeholders.

The derivation of future-oriented value added statements, like the derivation of the free cash flow in value-based management, is embedded into forecasted income statements and balance sheets (Berk and DeMarzo, 2020, p. 729-737; Koller et al. 2020, p. 229-251; Penman, 2022, p. 480-492; Rappaport, 1998, p. 68). Accordingly, the discounted value added approach uses the same information base, which enables its integration into value-based management. From the internal forecast calculations, the successes of the equity and debt holders can be directly derived, whereas the determination of the successes of the workers and the community requires the application of a more differentiated value driver model. In order to determine an appropriate level of complexity for the underlying value driver model, the corresponding increased information costs must be weighed against the benefits for sustainability management. It should be noted that the use of value added statements and the discounted value added approach can support the shift from a shareholder-oriented mindset to a stakeholder-oriented mindset with a corresponding beneficial change in corporate culture (Bagieńska, 2017, p. 93; Dierkes et al. 2016, p. 238; Haller, 1997, p. 4-20).

The discounted value added approach takes into account the interdependencies between the value added creation and distribution, whereas value-based management analyzes the impacts of a business strategy mainly from the perspective of the equity holders. The discounted value added approach determines the single- and multi-periodic consequences for the successes of the workers, community, equity holders, and debt holders. Thus, it can provide sustainability management with comprehensive information on the future consequences of business strategies (Dierkes et al. 2016, p. 243). In addition, the discounted value added approach detects trade-off relationships among the four stakeholders and can determine the success that is redistributed among stakeholder groups by a business strategy. For an initial analysis of stakeholder value creation and distribution, we can calculate value added- and stakeholder-related key ratios on an aggregate level: The stakeholder value and the market values of the successes of the four stakeholder groups are suitable as absolute key ratios, whereas the shares of the four interest groups on the stakeholder value can be used as relative key ratios. However, this is only the starting point for more detailed analyses of value creation and distribution. While the focus of the following analyses is on the economic and social dimensions of sustainability, we will also briefly address the possibility of providing environmentally relevant information.

4.3.2 Analysis of the stakeholder value creation

An analysis of the stakeholder value creation provides sustainability management information on a company's value added sources and its potential for economic and social success. The stakeholder value creation can be analyzed regarding organization-, market-, product-, time-, and payment type-related analysis criteria, as illustrated in Table 15. These criteria can be used alone in single-dimensional analyses or combined in multi-dimensional analyses as well as for the development of value added-related key ratios.

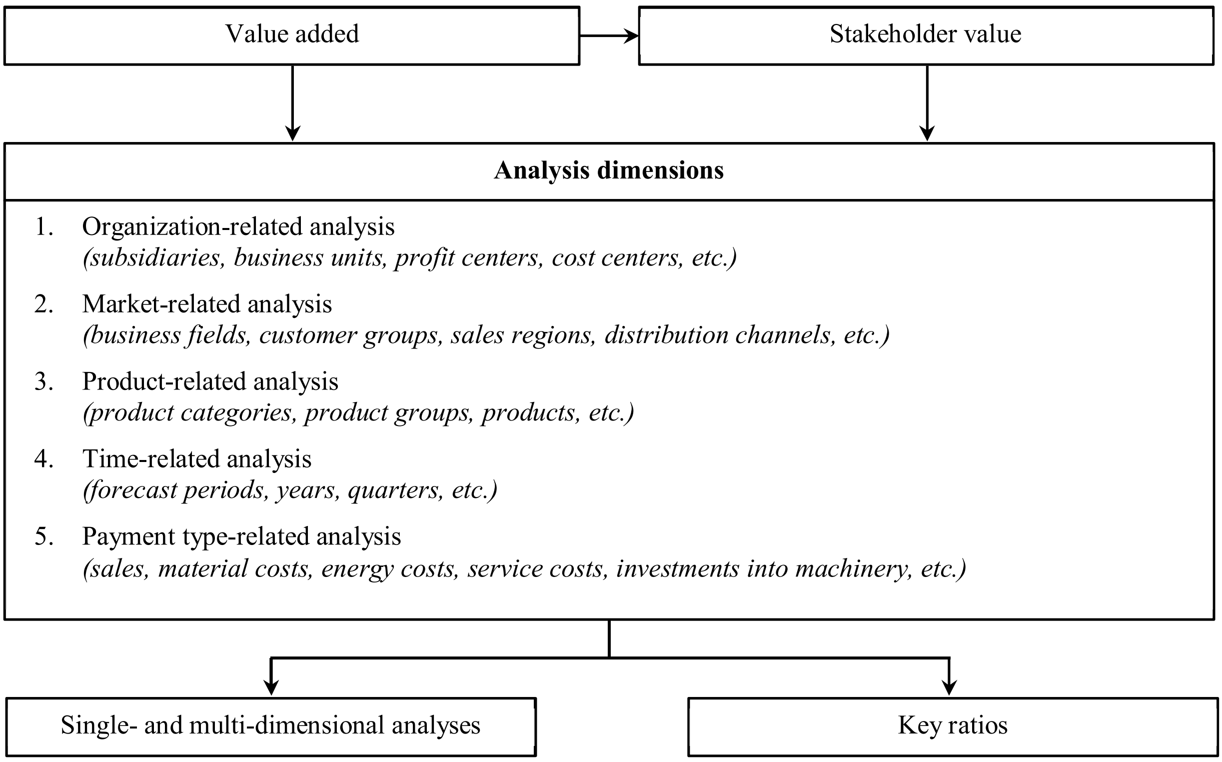

Table 15: Analysis of the stakeholder value creation

An organization-related analysis answers questions regarding the contributions of a company's organizational units, such as business units, profit centers, or cost centers to the creation of the stakeholder value (Berk and DeMarzo, 2020, p. 272-280; Koller et al. 2020, p. 98-106). From a market-related analysis, sustainability management can obtain information on a company's major sales markets and customer groups and their share of the stakeholder value. Moreover, it can be examined which products are responsible for the creation of a company's stakeholder value. In this context, it is also possible to obtain some environmental information. For example, the stakeholder value can be divided among a company's sustainable and non-sustainable products, which requires a corresponding categorization of products based on environmental and social criteria. The EU Commission provides a possible basis by defining criteria for classifying sustainable corporate activities that contribute to environmental and climate goals (European Commission, 2021). A time-related analysis shows the development of the stakeholder value or the periodic value added over time. Finally, a payment type-related analysis informs on the single components of the stakeholder value. It consists of the market value of the production value as well as the market value of the bought-in products and services. The production value summarizes a company's sales and changes in inventory and the bought-in product and services include payments for different materials, energies, intermediate products, and services types (Haller, 1997, p. 58; Weber, 1980, p. 6-9; Wenke, 1987, p. 92). The payment type-related analysis can also provide additional environmental information if, for example, payments for renewable and non-renewable energy or payments for waste, rejects, reworking, and recycling are determined separately. Furthermore, it can be analyzed which bought-in products and services a company purchases from local or sustainability-certified suppliers (GRI, 2020; SASB, 2017).

The one-dimensional analysis can be used to determine both absolute key ratios, such as the stakeholder value of a business unit or product, and relative key ratios, such as the share of a business unit or customer group value on the stakeholder value. Further information can be obtained from a multi-dimensional analysis that combines different analysis dimensions, as known from multi-level contribution margin accounting (Coenenberg et al. 2016, p. 231; Ewert and Wagenhofer, 2014, p. 672; Friedl et al. 2022, p. 420). For example, by using market- and product-related analysis criteria, we can determine the stakeholder value of sustainable product sales in the European, American, or Asian markets.

4.3.3 Analysis of the stakeholder value distribution

The analysis of the stakeholder value distribution provides sustainability management with information about the drivers and structure of the successes of the workers, community, equity holders, and debt holders. The four stakeholders consist of heterogeneous subgroups with different objectives. Therefore, the stakeholder value distribution can be analyzed not only on the level of the four stakeholders but also on the level of their subgroups. For the analysis, we use stakeholder value creation-, time-, distribution-, and payment type-related criteria, as illustrated in Table 16. Since equity and debt holders have been analyzed in detail in value-based management, we have combined them into one group. The analysis criteria can be used for single-dimensional and multi-dimensional analysis and for the development of stakeholder-related key ratios.

Flow to a stakeholder → Market value of the flow to a stakeholder

Analysis dimensions			
	Workers	Community	Equity and debt holders
Stakeholder value creation-related analysis	*business units, sales markets, production sites, product groups, products, etc.*		
Time-related analysis	*forecast periods, years, quarters, etc.*		
Distribution-related analysis	*employment types, wage groups, gender, nationalities, seniority, age structure, etc.*	*states, federal states, regions, public institutions, NGOs, clubs, associations, etc.*	*investor types, capital types, ownership structure, countries, etc.*
Payment type-related analysis	*wages, social security contributions, further education costs, employee-related investments, etc.*	*corporate taxes, fees, duties, donations, penalty payments, community-related investments, etc.*	*dividends, interests, debt repayments, debt borrowing*

Single- and multi-dimensional analyses

Key ratios

Table 16: Analysis of the stakeholder value distribution

A stakeholder value creation-related analysis and a time-related analysis can be done for all four stakeholders. A stakeholder value creation-related analysis shows, for example, how business units, products, or production sites contribute to the success of the workers or the community. A time-related analysis of the market value of the flow to worker provides information on the relevance of forecast periods for value creation. Therefore, both analysis criteria are helpful for analyzing the stakeholder value distribution. The other two analysis criteria can also be applied to all stakeholders, but their specific design depends on the stakeholder group.

In a distribution-related analysis, the market value of the flow to worker can be subdivided among different subgroups, such as employment types, wage groups, nationalities, and seniority. Furthermore, the workers' success can be attributed to employee gender to provide business decision-makers with information relevant for diversity management (Duff, 2016, p. 80; Searcy et al. 2016, p. 2914). Finally, a payment type-related analysis investigates the single components of the market values of employee-related payments and employee-related investments. The employee-related payments contain payment types such as wages, health insurance contributions, further education costs, training costs, and security costs (Duff, 2016, p. 80; International Integrated Reporting Council, 2013; Searcy et al. 2016, p. 2914; Ziehm, 1978, p. 129-138). The employee-related investments include payments for specially designed machineries that reduce the physical workload of the employees, as well as investments into company-owned kindergartens, cafeterias, or apartments (Aldama and Zicari, 2012, p. 490; Kuasirikun and Sherer, 2004, p. 638).

The success of the community is distributed among different subgroups, such as countries, federal states, regions, public institutions, NGOs, clubs, and associations. Therefore, a corresponding distributed-related analysis sheds light on the funding of public services and the promotion of societal life (GRI, 2020; SASB, 2017). From a payment type-related analysis, sustainability management obtains information on the single success components of the community. The community-related payments consist, for example, of donations, fees, and customs duty, while the community-related investments include all corporate investments that generate a common benefit for the company and the community (Aldama and Zicari, 2012, p. 490; Coenenberg et al. 2021, p. 552-553; Duff, 2016, p. 80; GRI, 2020; Kieso et al. 2022, p. 987; Vuorinen and Martinsuo, 2019).

In past decades, the successes of equity and debt holders have been intensively investigated in value-based management (Hillier et al. 2020; Koller et al. 2020; Rappaport, 1998). Nevertheless, the analysis of the stakeholder value distribution can even provide information on the equity and debt holders. In a distribution-related analysis, the equity and debt market values are investigated regarding their distribution among subgroups, such as equity and debt investor types, capital types, ownership structure, and countries (Brealey et al. 2019, p. 606; Hillier et al. 2020, p. 557-559). A payment type-related analysis provides sustainability management with knowledge of the components of the equity and debt market values, such as dividends, interests, debt repayments, and debt borrowing (Berk and DeMarzo, 2020; Rappaport, 1998; Strack and

Villis, 2001).

The distribution of the stakeholder value includes besides economic and social information also some environmental knowledge. The remuneration of employment types, such as environmental officers or heads of the recycling cost centers, possesses an environmental reference (GRI, 2020; SASB, 2017; Ziehm, 1978, p. 129). Moreover, further education costs for environment-related seminars and the private use of an electric company car as well as sewage fees and environment-related donations are environmental success components of the workers and community. Even the equity and debt market values include environmental information, because some equity and debt holders depend for their investment decisions on the environmental impacts of a company (Ballwieser and Hachmeister, 2021). Thus, a company's environmental performance influences the structural composition of equity and debt capital.

Finally, the single analysis dimensions of the stakeholder value distribution can be used for the development of stakeholder-related key ratios as well as for multi-dimensional analyses. Therefore, the market values and the successes of all stakeholders can be subdivided into various absolute and relative stakeholder-related key ratios. For example, we can determine the market value of the flow to worker per employment type or per production site. Considering the number of employees or full-time equivalents, these absolute key ratios can be converted into relative key ratios (Strack and Villis, 2001; Fitz-Enz, 2009; Fischer and Vielmeyer, 2002). Such analyses can be done for all stakeholders, illustrating the usefulness of the discounted value added approach in sustainability management.

4.4 Conclusion

Sustainability management has to align business activities to economic, social, and ecological goals. This requires new information instruments, as most of the existing ones are developed for value-based management with a focus on shareholders' objectives. Our new discounted value added approach provides information about the impact of the management decisions on the goals of selected stakeholders of a company. Its main characteristic is embedding future-oriented value added statements into the discounted cash flow approach, which enables the determination and analysis of stakeholder value and its distribution among selected stakeholders.

In contrast to value added statements in sustainability reporting, we used value driver models to forecast cash flow-oriented value added statements. Compared to the well-known value driver models in value-based management, we need more complex value driver models for the analysis of the creation and distribution of the value added with the four stakeholder groups workers, community, equity holders, and debt holders. Embedding the cash flow-oriented value added statements into discounted cash flow approaches enables the determination of the stakeholder value with its distribution to the stakeholders. This information instrument can be used in sustainability management to analyze the impacts of short- and long-term decisions on value creation and distribution, allowing the identification of interdependencies and trade off-relationships. We presented several single- and multi-dimensional analyses for analyzing the stakeholder value creation and distribution. The results of these analyses can be condensed into key ratios useful for decision-making and behavioral control in sustainability management, particularly in the economic and social dimensions, but additionally also in the ecological dimension. However, the benefits of using the discounted value added approach must be weighed against the additional information costs. Still, the possible shift from a shareholder-oriented mindset towards a stakeholder-oriented mindset of the employees should be considered.

The presented discounted value added approach can be further developed in several ways. In our approach, we have used an undifferentiated cost of capital to discount the created value added and distributed value added to workers and the community. In this respect, we need to explore the use of differentiated costs of capital. Furthermore, analogous to value-oriented ratios in value-based management, such as EVA or CVA, it should be analyzed how value added-oriented ratios can be determined to analyze the periodic creation of value added and its distribution among stakeholders. Finally, the approach should be extended from a single company to the entire value chain to consider the impacts of business decisions, especially on social and ecological goals. Overall, the discounted value added approach proved to be a promising information instrument for sustainability management that needs further development.

5. Conclusion

5.1 Summary and practical implications

For a stronger consideration of environmental and social impacts of a company's business activities, sustainability management relies on consistent sustainability information for corporate decision-making and behavioral control. The provision of such economic, environmental, and social knowledge is a responsibility of sustainability controlling that uses appropriate information tools for this purpose. However, the existing controlling instruments that are frequently applied in corporate practice primarily focus on the financial success of the equity and debt holders and, thus, have limited use for sustainability management. Therefore, it is necessary to develop information tools that can provide sustainability management consistent economic, environmental, and social information. For this reason, the three studies of this thesis were focused on the further development of material flow cost accounting and value added statements that can assist sustainability management in different ways.

The first study, *Production and Cost Theory-Based Material Flow Cost Accounting*, developed a material flow model that provides a production and cost theory foundation for material flow cost accounting. This foundation made the relationships between material flow cost accounting and other environmental cost accounting systems more transparent and thereby simplifies the introduction of this environmental cost accounting tool to corporate practice. Furthermore, the study demonstrated the application of material flow cost accounting as a planning tool, whereas it is mostly described in literature as an actual cost accounting system (Chompu-inwai et al., 2015; Mahmoudi et al., 2017; May and Günther, 2020). Besides the stepwise budgeting of the efficient and inefficient material demand at the company, quantity center, and product unit levels, this study provided new insights into the calculation process of the quantity center costs as well as the composition and sources of the material and product losses. Moreover, the description of the secondary cost accounting and the separate assignment of efficient and inefficient costs to the single product units provide useful information on the creation of unintended co-products such as waste and rejects to sustainability management. With this knowledge, sustainability management can identify quantity centers, where the material and product losses occur and determine their quantitative and monetary levels. This information can be used to initiate projects for the reduction of the material and product losses and guide the behavior of the responsible quantity center owners with monetary incentive systems, towards a reduction of the material and product losses and, thus, toward resource efficiency.

The second study, *Material Flow Cost Accounting with Multiple Inefficiency Factors*, developed a material flow model that includes different inefficiency factors and environmental protection measures used for the development of the material flow cost accounting system for the budgeting of the manufacturing, recycling, and disposal costs. The material flow model included the opposing effects of waste and rejects as well as reworking and recycling on the material demand, which enabled a more precise forecast of the efficient, inefficiency decreasing and inefficient material and energy flows. Moreover, it enabled the evaluation of the environmental protection measures at the company, quantity center, and product unit levels. The development of the product- and material-oriented input-output tables provided deep insights into the material flows entering and leaving the manufacturing, recycling, and disposal quantity centers. Furthermore, the detailed description of the budgeting of the manufacturing, recycling, and disposal quantity center costs revealed their main cost drivers and clarified the composition of the four cost categories. It also clarified the treatment of the material and product losses inside a company and demonstrated the interrelationship of a company's quantity centers. Moreover, the separate disclosure of the cost increasing and decreasing impacts of the single inefficiency factors and environmental protection measures provided a better understanding of the structure of the product unit costs and, thus, made a differentiated analysis of a company's environmental protection measures possible. Finally, the behavioral guiding effects that results from the use of the material distribution key and further development opportunities for this cost accounting system became clear.

The third study, *Development and Application of the Discounted Value Added Approach in Sustainability Management*, showed the conception of a stakeholder-oriented valuation approach for the measurement of the stakeholder value and the successes of the involved stakeholder. This new valuation approach incorporated the goals of the different interest groups in decision-making and behavioral control. The study was developed on the basis of pre-existing internal forecast calculations and a suitable value driver model for future-oriented cash flow-based value added statements that were used for the calculation of the stakeholder value creation and distribution. The stakeholder value is determined through the creation calculation of the discounted value added approach by discounting the future value added of an infinite time horizon with appropriate costs of capital. In the distribution calculation, the market value is distributed among the workers, community, debt holders, and equity holders and thus provides insights into the level and composition of these stakeholders' future successes. Moreover, the analysis of the economic and social consequences of the stakeholder value creation and distribution contributed new stakeholder- and value added-related information to sustainability management and thus enabled a stronger consideration of the stakeholders' interests in corporate decision-making. Finally, the analysis of the stakeholder value and the successes of the four interest groups enabled the calculation of value added- and stakeholder holder-related key ratios that can provide sustainability management short- and long-term information on the impacts of a company's business activities.

5.2 Limitation and outlook

This thesis and its three studies have different types of limitations that are related to particular features of the discussed information instruments. The limitations are theoretical and practical and concern both material flow cost accounting and the discounted value added approach. However, despite the limitations outlined in this chapter, both instruments have a wide range of possibilities for their further conceptual development.

In material flow cost accounting, it is indirectly assumed that the material and product losses of a company can generally be avoided. But the reduction of the material and product losses is possible only up to a technical minimum and thus does not automatically lead to the avoidance of all losses. A further reduction of the inefficient costs beyond this minimum level is only possible through closer cooperation among a company's supply chains (ISO, 2011, p. 8; Schrack, 2016, p. 199). Accordingly, the disclosure and use of material and product loss-related information without the consideration of the technical possibilities in corporate production processes lead to wrong decisions. Additionally, material flow cost accounting does not differentiate the material and product losses according to their environmental harmfulness. However, for a fast and effective relief of the environment, sustainability management should first address the most harmful material and product losses.

Furthermore, material flow cost accounting analyzes all material and energy flows and their transformation processes and, thus, has high requirements for a company's operational data management (Strobel, 2001). The construction and maintenance of an advanced data management system for tracking the material and energy flows are associated with comparatively high initial investments and ongoing costs, which represent a significant barrier for the introduction of this cost accounting tool, especially for small companies (Kokubu and Kitada, 2015; Sulong et al., 2015). Therefore, the developed material flow cost accounting systems seem to be more suitable for a project-based implementation in large companies than for a regular industry-wide introduction.

Finally, in this thesis, the creation of the material and product losses is traced back to the four influencing factors: waste, rejects, reworking, and recycling. However, in corporate practice, additional inefficiency factors such as production intensity, material quality, and human error occur in the transformation processes. Accordingly, the material flow model needs to be supplemented by these additional inefficiency factors in order to provide more realistic explanations for the emergence of material and product losses. In this context, it can also be questioned whether the occurrence of the material and product losses can always be attributed in corporate practice to a single inefficiency factor. In the second study, it was assumed that product defects are immediately detected after the transformation process and thus no further quantity center and material costs occur. But product defects are mostly identified after several production steps and therefore additional costs are created with rejected products (Kilger et al., 2012, p. 234-240).

For future research, the development of a differentiated contribution margin accounting is also necessary if a material flow cost accounting system focuses only on the variable costs of a company's material and product losses. Another promising approach is the expansion of material flow cost accounting from a single company towards the entire value chain (Schrack, 2016, p. 199). This allows, at each value added stage, for a more detailed evaluation of the environmental impacts of the created products as well as material and product losses and their associated costs. However, this requires a detailed and constant data flow between all companies that belong to the value added chain. Moreover, externalized effects from corporate business activities can be integrated into material flow cost accounting to measure all economic and environmental impacts related to a company's material and product losses.

The study on the development of the discounted value added approach and its use in sustainability management is also subject to a few limitations. The first limitation is related to the value driver model used in sustainability management. The discounted value added approach depends on the forecast of the future value added creation and distribution on an appropriate value driver model that predicts the value added and the successes of the stakeholders. The structure of such a differentiated value driver model has not been described in the literature before. Moreover, corresponding planning efforts of such a detailed value driver model lead to comparatively high time and resource expenditures, which can be an obstacle for the introduction of this management tool in corporate practice.

Furthermore, the discounted value added approach uses weighted costs of capital for discounting the future value added and the successes of the workers and the community. The weighted costs of capital consist of the cost of equity and debt weighted by the equity and debt ratio. But for determining the market value, it is common to use stakeholder-specific costs of capital, as it is known from valuation literature (Diedrich and Dierkes, 2015; Koller et al., 2020). Nonetheless, costs of capital for the workers and the community can be derived neither from the financial capital nor from the labor market. However, to ensure a complete integration of this new value added-oriented valuation tool into the discounted cash flow approaches, the determination of stakeholder-specific costs of capital is necessary.

The final limitation concerns the stakeholders' non-monetary goals. In the discounted value added approach, the market values of the stakeholders' future successes consist only of their financial goals. However, stakeholders have further social and environmental objectives that cannot be monetized and are, consequently, not considered in this valuation approach. For this reason, the discounted value added approach cannot provide useful information for sustainability management, if the successes of the stakeholder primarily concern their non-financial goals.

The discounted value added approach has many opportunities for future enhancement. Additional interest groups, such as customers, suppliers, and the environment, can be incorporated into the distribution calculation (GRI, 2020, p. 51; SASB, 2017, p. 2-8). The discounted value added approach can also be expanded from a single company to the entire value added chain of products to provide sustainability management information on the successes of the stakeholders at each value added stage. Finally, the discounted value added approach should capture not only the internalized effects of a company's business activities but also the external effects.

In summation, the two instruments represent with their particular characteristics and the creation of economic-environmental as well as economic-social information a benefit for sustainability management and accordingly supplement the already existing set of information tools of sustainability controlling. However, for corporate decision-making and behavioral control in corporate practice, decision-makers rely on the combined use of the different controlling instruments to obtain comprehensive knowledge of a company's sustainability impacts. Nevertheless, one has to keep in mind that there is still a need for conceptual further development of the information tools to provide sustainability management appropriate information to meet a company's future economic, environmental, and social challenges.

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Versicherung

Ich versichere,

1. dass ich die eingereichte Dissertation

„***Development of Material Flow Cost Accounting and Value Added Statements as Planning Instruments for Sustainability Management***“

selbstständig angefertigt habe und nicht die Hilfe Dritter in einer dem Prüfungsrecht und wissenschaftlicher Redlichkeit widersprechenden Weise in Anspruch genommen habe,

2. dass ich das Prüfungsrecht einschließlich der wissenschaftlichen Redlichkeit – hierzu gehört die strikte Beachtung des Zitiergebots, so dass die Übernahme fremden Gedankenguts in der Dissertation deutlich gekennzeichnet ist – beachtet habe,

3. dass beim vorliegenden Promotionsverfahren kein Vermittler gegen Entgelt eingeschaltet worden ist sowie im Zusammenhang mit dem Promotionsverfahren und seiner Vorbereitung kein Entgelt gezahlt oder entgeltgleiche Leistungen erbracht worden sind keine Dienste unentgeltlich in Anspruch genommen wurden, die dem Sinn und Zweck eines Prüfungsverfahrens widersprechen,

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Mir ist bekannt, dass Unwahrheiten hinsichtlich der vorstehenden Versicherung die Zulassung zur Promotionsprüfung ausschließen und im Falle eines späteren Bekanntwerdens die Promotionsprüfung für ungültig erklärt werden oder der Doktorgrad aberkannt werden kann.

Göttingen, den 22. Dezember 2022

(David Siepelmeyer)

Erklärung zum Eigenanteil der Dissertationsschrift

Paper 1: "*Production and Cost Theory-based Material Flow Cost Accounting*"

Dieser Artikel ist in Zusammenarbeit mit Prof. Dr. Stefan Dierkes entstanden. Die Entwicklung des Materialflussmodelles und die Konzeption des Kostenrechnungssystems erfolgte im Austausch mit Prof. Dierkes. Allein verantwortlich war ich für die Analyse der Materialflüsse in den Mengenstellen, der Allokation der Materialflüsse zu den Produkten, Beschreibung der Mengenstellenplanung sowie der Erstellung des Literaturüberblicks und des Verfassens des größten Teils des Textes.

Paper 2: "*Material Flow Cost Accounting with Multiple Inefficiency Factors*"

Dieser Artikel ist in Zusammenarbeit mit Prof. Dr. Stefan Dierkes entstanden. Die Entwicklung des Materialflussmodelles und die Konzeption des Kostenrechnungssystems erfolgte im Austausch mit Prof. Dierkes. Allein verantwortlich war ich für den Literaturüberblick, die Analyse der Materialflüsse auf Mengenstellen- und Produktebene, die Erstellung der material- und produktorientierten Input-Ouput Analysen, die Ermittlung des Materialbedarfs der Produkte, die Beschreibung der Mengenstellenplanung sowie das Verfassen des größten Teils des Textes.

Paper 3: "*Development and Application of the Discounted Value Added Approach in Sustainability Management*"

Dieser Artikel ist in Zusammenarbeit mit Prof. Dr. Stefan Dierkes entstanden. Die Entwicklung des Bewertungsansatzes und des theoretischen Rahmens erfolgte im Austausch mit Prof. Dierkes. Allein verantwortlich war ich für die Erstellung des Literaturüberblicks, die Konzeption von planungsbasierten Wertschöpfungsrechnungen, die Herleitung des Bewertungsverfahrens, die Analyse der Entstehung und Verteilung des Stakeholder Value sowie das Verfassen des größten Teils des Textes.

Göttingen, den 22. Dezember 2022

(David Siepelmeyer)