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Production and cost theory-based material flow cost accounting

Stefan Dierkes*, David Siepelmeyer

Chair of Finance and Control, Georg-August University, Platz der Göttinger Sieben 3, 37073, Göttingen, Germany

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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.

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, 2013; 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

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* Corresponding author.
E-mail addresses: stefan.dierkes@wiwi.uni-goettingen.de (S. Dierkes), david.siepelmeyer@wiwi.uni-goettingen.de (D. Siepelmeyer).

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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. Production theory-based material flow model

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 $j = 1, \ldots, J$. 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 $m = 1, \ldots, M$. 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):

$$r'_m = a'_{m,1} \cdot r'_1 + \ldots + a'_{m,M} \cdot r'_M + a'_{m,M+1} \cdot r'_{M+1} + \ldots + a'_{m,M+J} \cdot r'_{M+J} + xa_m + \Delta l_m \quad \text{with } m = 1, \ldots, M \tag{1}$$

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

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 r' denotes the vector of the required quantity of materials and products, A' represents the matrix of production coefficients, xa stands for the vector of product sales volumes, and Δl denotes the vector of changes in inventories:

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

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

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

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:

$$r_m = a_{m,1}\cdot r_1 + \ldots + a_{m,M}\cdot r_M + a_{m,M+1}\cdot r_{M+1} + \ldots + a_{m,M+J}\cdot r_{M+J} + xa_m + \Delta l_m + \beta_m \cdot r_m \quad \text{with } m = 1,\ldots,M \tag{5}$$

$$r_{M+j} = a_{M+j,1}\cdot r_1 + \ldots + a_{M+j,M}\cdot r_M + a_{M+j,M+1}\cdot r_{M+1} + \ldots + a_{M+j,M+J}\cdot r_{M+J} + xa_{M+j} + \Delta l_{M+j} + \beta_{M+j}\cdot r_{M+j} \quad \text{with } j = 1,\ldots,J \tag{6}$$

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

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

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 Fig. 1.

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

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

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 $b'_{m,M+j}$:

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

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. 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:

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

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

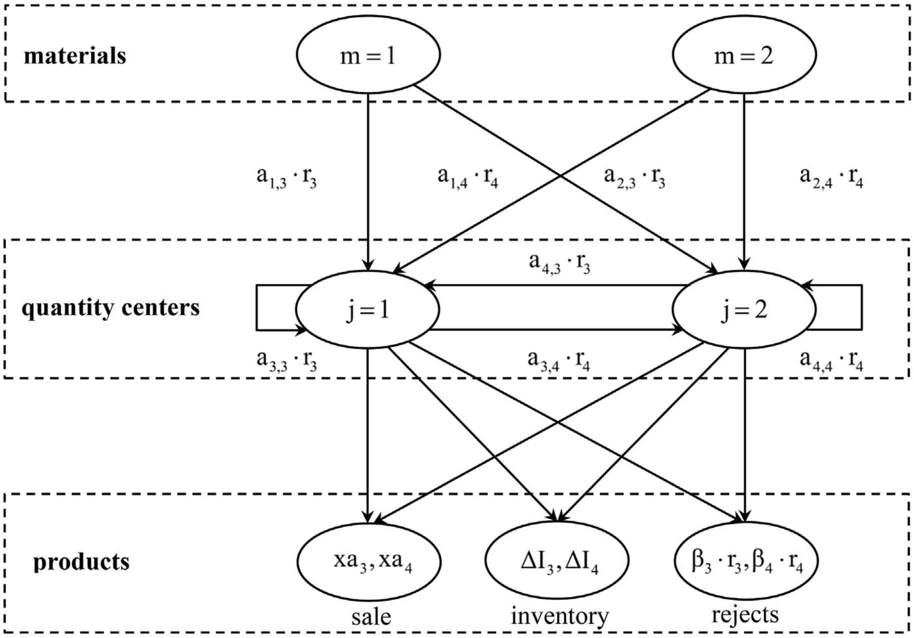


Fig. 1. Material flow model with two materials, quantity centers, and products.

of the primary and secondary material demand $r^*_{m,M+j}$ of quantity center $M+j$:

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

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 $re_{m,M+j}$:

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

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

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:

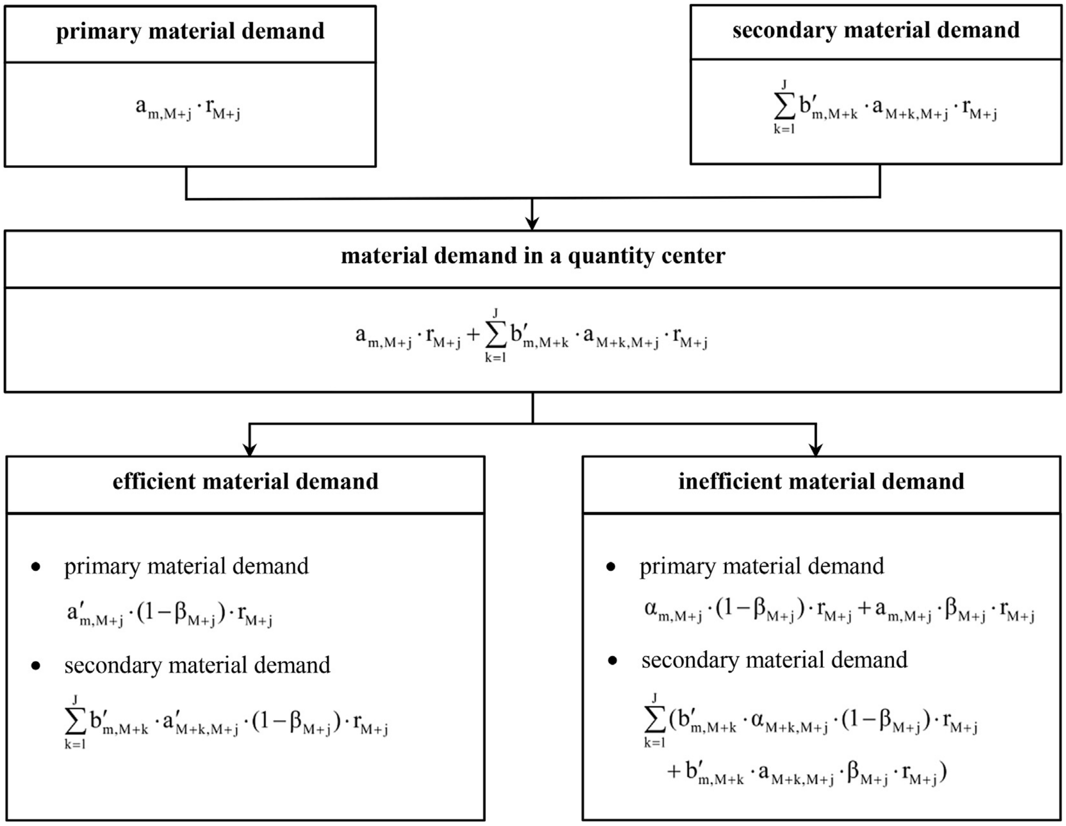


Fig. 2. Primary, secondary, efficient, and inefficient material demand in a quantity center.

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 Fig. 2.

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.

2.3. 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 2.1. 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.

3. Conception and application of a material flow cost accounting system

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 costs 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.

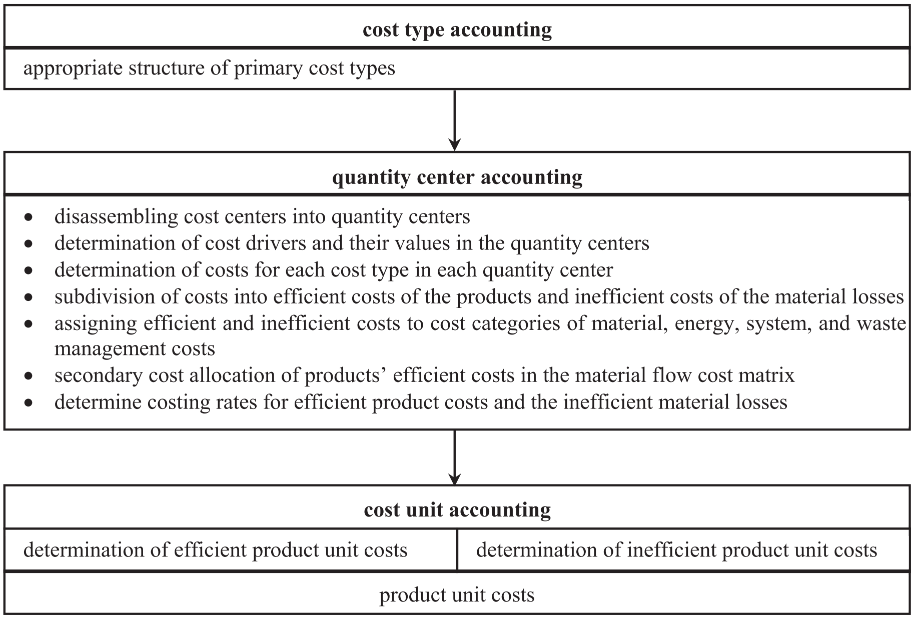
To consider the performance relationships between different quantity centers, MFCA includes a specific type of secondary cost allocation with the material flow cost matrix. In the literature on MFCA, the relationship between the material flow cost matrix and conventional secondary cost accounting is 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 Fig. 3. 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.

In this MFCA structure, we separate costs using the three dimensions of cost types, cost efficiency, and cost categories, which is shown in Fig. 4. 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).

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, 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.

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



cost type accounting

appropriate structure of primary cost types

quantity center accounting

- disassembling cost centers into quantity centers
- determination of cost drivers and their values in the quantity centers
- determination of costs for each cost type in each quantity center
- subdivision of costs into efficient costs of the products and inefficient costs of the material losses
- assigning efficient and inefficient costs to cost categories of material, energy, system, and waste management costs
- secondary cost allocation of products' efficient costs in the material flow cost matrix
- determine costing rates for efficient product costs and the inefficient material losses

cost unit accounting

determination of efficient product unit costs

determination of inefficient product unit costs

product unit costs

Fig. 3. Structure of material flow cost accounting as a full cost accounting system.

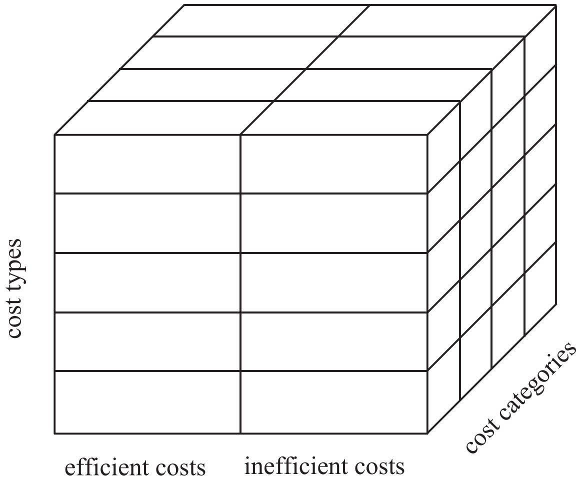


Fig. 4. Cost types, cost efficiency, and cost categories as cost dimensions.

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 (ISO, 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.

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

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

	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 2
Cost category-oriented product unit costing calculation scheme.

	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)

can be further disaggregated using the other two dimensions.

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.

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.

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

	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)

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 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 3.1, but some adjustments are necessary.

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

	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)

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 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.

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.

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