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Material flow accounting and the efficient use of resources

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Abstract

This study presents a comprehensive theoretical analysis of Material Flow Cost Accounting (MFCA) and demonstrates its application within the mining industry. The primary objective is to reveal the conceptual foundations and potential of MFCA and demonstrate its value as a tool for enhancing resource efficiency in industrial operations. The analysis uses scientific methods, including abstraction, analysis, synthesis, and mathematical techniques, such as matrix and vector mathematics, for modelling material flows. Following the theoretical discussion, a practical example from the mining industry is presented to illustrate how MFCA can be applied in identifying inefficiencies, such as waste generation and cost accumulation. The results show that MFCA, through structured analysis of material and energy flows, offers a solid framework for technological decisions, that are aimed to reduce inefficiencies and improving resource utilisation. One specific application discussed is the use of heat pumps to recover thermal energy from wastewater, which could be repurposed to heat nearby mining settlements.

Zusammenfassung

Diese Studie bietet eine umfassende theoretische Analyse der Materialflusskostenrechnung (MFCA) und illustriert ihre Anwendung anhand eines Modellbeispiels aus der Bergbauindustrie. Das Hauptziel besteht darin, die konzeptionellen Grundlagen und das Potenzial von MFCA als Instrument zur Analyse und Optimierung von Ressourceneffizienz in industriellen Prozessen aufzuzeigen. Bei der Analyse werden wissenschaftliche Methoden wie Abstraktion, Analyse und Synthese sowie mathematische Techniken wie Matrix- und Vektormathematik zur Modellierung von Materialflüssen eingesetzt. Im Anschluss an die theoretische Diskussion wird ein praxisorientiertes Beispiel aus der Bergbauindustrie vorgestellt, um zu veranschaulichen, wie MFCA bei der Identifizierung von Ineffizienzen, wie z. B. Abfallentstehung und Kostensteigerung, unterstützen kann. Die Ergebnisse zeigen, dass MFCA durch die strukturierte Analyse von Material- und Energieflüssen eine fundierte Grundlage für technologische Entscheidungen bietet, welche die Ineffizienzen verringern und die Ressourcennutzung verbessern können. Ein spezifisches Beispiel ist die Nutzung von Wärmepumpen zur Rückgewinnung thermischer Energie aus Abwasser, die zur Beheizung nahe gelegener Bergarbeitersiedlungen genutzt werden könnte.

Statutory declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Vienna, 22.12.2024 Karyna Onachenko

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Chapter 1 Introduction

Due to the increasing emphasis on sustainability and resource efficiency, the material flow cost accounting (MFCA) method of accounting is gaining more attention (Boons, 1998; Byrne & O'Regan, 2016; Chompu-inwai et al., 2015). Characterised by its comprehensive strategy of incorporating environmental and financial factors into business decisions, it aims to enhance resource efficiency and promote sustainability. In 2011, the International Organization for Standardization (ISO) proposed a general framework for material flow cost accounting. It is a standardized approach, which has since promoted broader adoption and integration of MFCA into sustainability strategies, making it more accessible and applicable for organizations worldwide. Recent developments towards a sustainable economy indicate the increasing relevance of MFCA and have fuelled the scientific debate on this topic (Bringezu & Moriguchi, 2018; Brunner & Rechberger, 2016; Laner et al., 2014; Walz & Guenther, 2021). MFCA promotes greater transparency in material and energy practices by improving the materials flow model, which tracks and quantifies material flows and quantities within an organisation in physical units. Any costs caused by the use of material and energy flows are then quantified and attributed to the costs of these flows. An important part of MFCA involves evaluating the costs linked to products in comparison to those related to residual outputs, including waste, air emissions, and wastewater.

Therefore, the application of MFCA is especially effective in industries potentially facing major environmental consequences due to material losses during manufacturing processes - such as metallurgical production, oil and mining, wood products, furniture production, etc. There MFCA can be used to identify inefficiencies and develop strategies to reduce waste and emissions.

However, the problem with the practical implementation of MFCA is that the practical use of this method could reveal issues that have so far been little analysed from a scientific point of view. In particular, it is generally believed that material flow cost accounting does not have a foundation based on production theory, unlike other established cost accounting systems. This makes its main use as an actual cost accounting system incomprehensible (Dierkes & Siepelmeyer, 2019). For the same reason, the impact of i.e. waste and rejects as well as rework and recycling, on the creation of material and product losses remains unclear. The difficulty also lies in how MFCA results can be integrated into material flow analysis and how subsequent recommendations for companies can be derived from this.

To gain this knowledge, material flow cost accounting must be combined with other tools (see Chapter 2.2.2.) to develop a system of planned material flow cost accounting based on production theory. This will enable the use of MFCA to plan the cost accounting for production costs, as well as material and product losses.

The goal of this master thesis is to expand the practical use of MFCA as a decision-making tool when analysing the distribution of costs across a company's material flows and finding ways to reduce the cost of waste generation. To achieve this, I analyse the concepts of material flows under the conditions of a sustainable development of a company and justify the choice of the MFCA concept. Based on Dierkes and Siepelmeyer (2019), the thesis explores the design of MFCA from a theoretical perspective. I highlight the production-theoretical foundations of MFCA and explain which information can be generated. Moreover, I discuss the use of MFCA as an instrument of material flow analysis. At the second stage, for the purpose of practical illustration of the application and use of the chosen concept, an example of using MFCA to calculate the distribution of costs across flows at a hypothetical mining enterprise is considered. Major factors of inefficiency in the enterprise's operation will be identified, it will be calculated how much production waste will cost the company and the potential profit increase highlighted, based on this information. In addition, he enterprise performance indicators will be determined independently.

The results of this study help to understand the theoretical development and practical implementation of MFCA. I show how firms can develop specific recommendations for reducing material and energy flows within the enterprise and their associated costs. This will make it possible to identify ways to reduce inefficiency factors and improve the economic and environmental performance of the enterprise.

Chapter 2 Theoretical foundations of material flow analysis and cost accounting

2.1 Corporate sustainability and material flows

To achieve stable and efficient operation of any company, it is necessary to ensure its corporate sustainability. According to Dyllick and Hockerts (2002), corporate sustainability of a company is an approach that creates long-term value for stakeholders by implementing a business strategy that considers all aspects of business performance in the social, environmental and economic spheres. This approach formulates a strategy for establishing a company, which is aimed at its prospective and effective development. In the paper of Steurer et al. (2005), corporate sustainability is considered as a model that guides corporations in their economic, social or environmental performance in the short and long term. In general, corporate sustainability is an indicator of trust of all stakeholders of the company (Kaptein & Wempe, 2001). Economic sustainability is characteristic of companies that can provide their shareholders with dividend payments above the average level. Environmental sustainability applies to companies that use natural resources in a way that consumption remains below the level of natural regeneration. Social sustainability refers to the company's activities aimed at enhancing human and social capital (Dyllick & Hockerts, 2002).

These three aspects of sustainable development goals must be weighted in accordance with a company's objectives, as decision-making in areas such as investment in production capacity, salary negotiations, or relocation of production sites impacts all three dimensions of sustainability. The literature distinguishes between the classical and economic approaches to the 'triple bottom line'. In the classical approach, all three sustainability dimensions are equally weighted, whereas in the economic triple bottom line approach, the economic dimension prevails over the environmental and social ones (Elkington, 1998; Müller-Christ, 2020). However, in corporate practice, the weighting of corporate objectives largely depends on various factors specific to the company and the respective decision-making situation. Therefore, companies striving for sustainable development should focus not just on financial indicators but on a triple bottom line. For effective corporate governance and decision-making, it is crucial to obtain objective information on the economic, environmental, and social factors that contribute to achieving these goals. Once a company's objectives are defined, sustainability management aligns all operational and financial activities with them, ensuring they address impacts across the entire value chain (Dierkes et al., 2016).

The main factors in managing sustainable development and corporate objectives are shown in Figure 1.

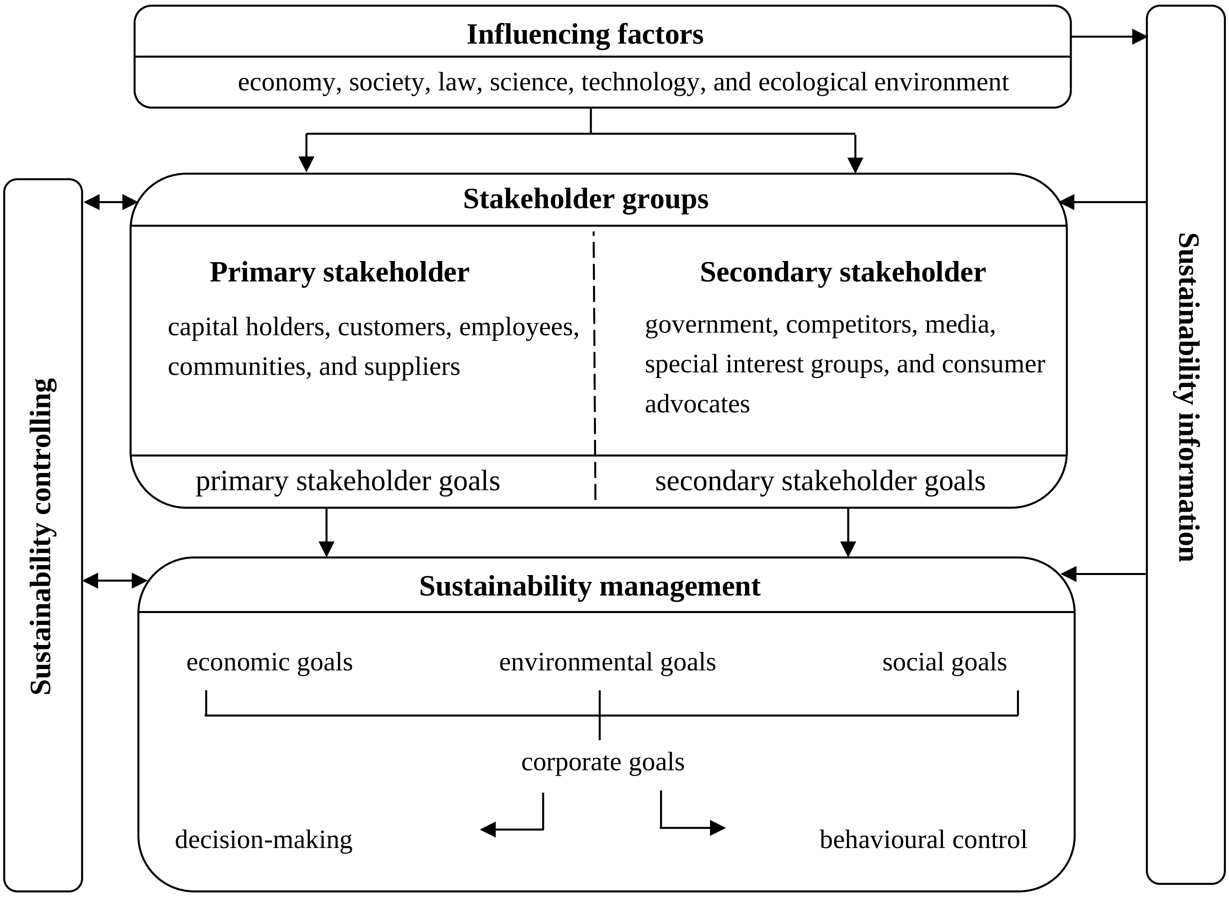


Figure 1. Sustainability management and corporate goals. Source: Siepelmeyer (2023).

It should also be taken into account that under EU law, all large companies and all listed companies (excluding listed micro-enterprises) are required to disclose information on risks, opportunities, and impacts related to social and environmental factors. This requirement aims to provide investors, civil society organisations, consumers, and other stakeholders with essential insights into companies' sustainability performance, aligning with the goals of the European Green Deal. These disclosures must comply with the Corporate Sustainability Reporting Directive (CSRD) - 2022/2464/EU and the Non-Financial Reporting Directive (NFRD) - 2014/95/EU.

The CSRD, effective as of January 5, 2023, updates and strengthens regulations on corporate social and environmental reporting. It expands the scope of reporting obligations to include large companies, listed small- and medium-sized enterprises (SMEs), and certain non-EU companies generating more than €150 million in EU market revenue. This directive aims to enhance transparency by ensuring stakeholders can assess companies' impacts on people and the environment, while also helping investors evaluate financial risks and opportunities related to climate change and sustainability issues (EU, 2022).

Finally, in the medium to long term, companies' reporting costs will be reduced by harmonising the information provided in line with EU standards. These standards apply to companies subject to the CSRD, regardless of the sector in which they operate. These standards integrate EU policy priorities while contributing to global standardisation initiatives. Additionally, the CSRD requires validation of the sustainability information that companies report and introduces a digital taxonomy to structure sustainability information systematically, ensuring its reliability and accessibility for decision-making (EU, 2022).

Corporate sustainability has evolved into a critical aspect of modern business operations. Companies that integrate tools for cost accounting and data transparency early will experience a smoother transition to the strict CSRD reporting frameworks. As businesses strive to meet these standards, tools and methodologies such as material flow analysis (MFA) play a pivotal role in supporting sustainable development.

2.2 Material Flow Analysis

2.2.1 The purpose of material flow analysis

The purpose of material flow analysis (MFA) is to systematically evaluate the movement of materials and substances within production processes, providing essential data for effective management of these flows. All production processes in an enterprise can be viewed as a system of material flows that, on the one hand, contribute to value creation, and on the other hand, result in material losses (i.e. defects and waste) generated during production. By mapping and analysing these flows, MFA helps identify inefficiencies, which can occur at various stages of production. This analysis is crucial for determining where losses are generated and how they can be minimised, contributing to a more efficient and streamlined process.

Accordingly, the primary goal of material flow analysis is to obtain information that can be used to manage production processes concerning the flow of materials, energy, and data. MFA supports organisations in not only enhancing production efficiency but also aligning their operations with long-term sustainability and resource optimisation goals. The insights gained through MFA serve as a foundation for better decision-making regarding production process improvements and strategic planning. By utilising MFA, companies can move toward more responsible resource management practices, contributing to economic performance improvements while simultaneously reducing their environmental footprint.

2.2.2 Instruments of material flow analysis

As mentioned above, corporate sustainability is based on the analysis of economic, environmental and social factors, making it inevitable to obtain objective information about these factors using appropriate tools, in order to achieve the company's goals. Focusing on the economic factor - for the analysis of which the classical cost accounting tools have been developed, nowadays a number of novel methods have been developed to expand the possibilities of traditional approaches. Additionally, there are management tools focusing on environmental and social aspects, as the need for environmental protection and rational use of natural resources sets quite specific tasks for companies to ensure their sustainable development. Equally important is the assessment of social impact, as it provides ways to address or reduce internal challenges within the company as a social entity. However, it is not always possible to connect the knowledge gained from analysing different factors through existing tools. Consequently, material and energy flow analysis methods are the most effective and appropriate tools for corporate decision-making and sustainable development management, as they provide consistent and cohesive information. The most renowned methods among these include MFCA (Christ & Burritt, 2015; Dierkes & Siepelmeyer, 2019; Nakajima, 2011; Schmidt & Nakajima, 2013), Input-Output Analysis (Dietzenbacher, 2004), Substance Flow Analysis (Huang et al., 2012; Markiewicz et al., 2017) and Life Cycle Assessment (LCA) (Hellweg & Milà i Canals, 2014; Phan et al., 2014; Weitz et al., 1994).

Material flow analysis is an analytical method that quantifies material flows in a well-defined system (Laner et al., 2014). It is used to study the flow of materials, substances or products across various industrial sectors (Schmidt & Nakajima, 2013). A critical aspect of MFA is its focus on waste identification, which aims to minimise material flow inefficiencies. By enabling the tracking of waste that is typically overlooked in economic analyses, MFA serves as a valuable tool for assessing the efficiency of material resource utilisation. This method is not only helpful in the field of industrial ecology but also lays the foundation for effective material flow management within organisations. Moreover, MFA is integral to Life Cycle Assessment (LCA), a methodology that evaluates the environmental impacts of products or services throughout their entire life cycle.

The environmental impact of a product or service is closely related to the fact that the mass of raw materials often significantly exceeds the mass of the final output. This discrepancy arises due to intermediate consumption, where the gross output, measured in physical terms, greatly surpasses the Gross Domestic Product (GDP). For instance, study of Brunner and Rechberger (2016) indicates that the resource extraction and processing involved in manufacturing frequently result in material flows that do not correlate directly with the economic value created, highlighting inefficiencies in resource use. To account for hidden material flows, Schmidt-Bleek (1998) proposed the concept of ecological backpack, which is an integral part of the holistic MIpS (Material input per unit of service) system. The "backpack factors" consist of five products: biotic materials, abiotic materials, water, air, and displaced soil. This concept represents hidden material flows and serves as a foundation for the material and energy resource flow calculations. The concept of ecological backpack provides tracking of material flows at all stages of the full life cycle of a product (raw material extraction, production of products, transportation, marketing); use (consumption, transportation, repair) and waste management (recycling, disposal). By highlighting these elements, the concept provides a comprehensive understanding of the inputs required for the production processes and the environmental impact associated with the extraction and use of these materials. The idea of hidden material flows emphasises the importance of accounting for all resources consumed in the production of goods, thus promoting a more sustainable approach to resource management.

A lifecycle resource accounting method known as "MIpS", or the "material footprint" approach, developed by the Wuppertal Institute for Climate, Environment, and Energy, focuses on quantifying the material resources required for a given service or product throughout its lifecycle. The conceptual and mathematical framework of MIpS, along with its historical development, was presented in an expanded publication by Saurat and Ritthoff (2013), building on the original manual by Ritthoff et al. (2002). This guide offered a step-by-step approach for calculating MIpS using MS Excel. Recent advancements in computing power and accessible lifecycle analysis software now enable researchers to calculate MIpS through matrix inversion, allowing for further refinement of MIpS models. Enhancements include system parameterisation, batch modelling for specific batches of production, and computational algorithms that improve data interpretation.

Saurat and Ritthoff's (2013) article provides a comprehensive review of the evolution of MIpS calculation methods and tools, illustrating ongoing advancements in this field. Despite these developments, Bringezu and Mostert (2019) noted the absence of an internationally standardised approach for calculating resource intensity across products. They argue that it is also essential to evaluate not only the materials directly used in production but also the indirect material costs associated with specific industries or enterprises, underscoring the need for a more holistic view of resource consumption in lifecycle assessments. This perspective broadens the utility of MIpS as an analytical tool within industrial ecology, supporting strategic decisions that minimise environmental impact by providing insight into the hidden flows of materials across the lifecycle of products and services.

Similar core aspects are adopted by the broader methodology of LCA, even though it benefits from established international standards. LCA is a comprehensive methodology for evaluating and analysing the environmental impact of a product across its entire lifecycle—from resource extraction and production to usage and disposal. By assessing every stage, LCA ensures a holistic evaluation of all inputs and outputs, minimising the risk of environmental impacts or emissions being shifted to different lifecycle phases (ISO, 2011). To accurately analyse environmental impacts, it is essential to include data on all materials, resources, and energy used throughout a product's lifecycle. While diverse LCA approaches vary in scope, objectives, and application, they are all based on standardised principles and methodology, primarily defined by ISO standards.

The LCA process is structured into four key stages:

- Goal definition, scope, and system boundaries, where products are selected and conditions for comparison are set
- Lifecycle inventory analysis, detailing the material and energy inputs and emissions at each stage
- Impact assessment, evaluating the inventory results for their environmental significance
- Interpretation, where lifecycle and impact assessment results are analysed for decision-making

Also, this approach considers the entire lifecycle of a product. Thus, in addition to the production system, further stages of the technological process, both upstream and downstream, are evaluated. Overall, when utilising resources and materials on one hand, and accounting for pollutant emissions on the other, it is essential to consider all relevant potential harmful impacts on soil, air, and water. A significant part of the effort in preparing an LCA is the search for suitable data. The resource-intensive data collection required for comprehensive models is often challenging. For manufacturing processes, it is crucial to rely on primary data that directly reflects the company’s resource usage, production, and waste streams (Jiang et al., 2020). Primary data provide the most accurate representation of material flows, allowing companies to identify inefficiencies and optimise resource management effectively. However, data related to the environment, especially for downstream processes, are very difficult to collect.

For many companies tracking the full product lifecycle is often impractical and falls outside their operational or sustainability interests. Downstream activities like waste recycling and resource recovery may be managed externally or do not significantly impact the company’s direct environmental or economic performance. As such, lifecycle stages beyond production are often considered unnecessary for their sustainability initiatives, as they do not align directly with their operational scope.

This is where material flow cost accounting becomes particularly relevant. MFCA, which is primarily characterised by the separate disclosure of information on product costs as well as material and product losses, was developed in the late 20th century. MFCA supports the analysis of material and energy flows to provide critical information for managing production processes, focusing on their economic and environmental impacts. In 2011, the International Standard ISO 14051:2011, Environmental Management—Material Flow Cost Accounting—General Framework, was introduced, providing a formal structure for the application of MFCA. According to ISO, the primary goal of MFCA is to identify opportunities for cost savings by reducing waste, emissions, and inefficient energy and material flows. This standard, along with subsequent research on material flows, has significantly expanded the use of MFCA by focusing on material losses occurring during production, allowing for the analysis of material and energy flow transformations within quantity centers - specific areas or processes where costs are accumulated and tracked (Jasch, 2008). These cost centers serve as units for analysing resource consumption, such as materials and energy, and identifying inefficiencies in production. By segmenting costs within these areas, companies can separately disclose the associated costs of materials, energy, systems, and waste management, thereby gaining detailed insights into the flow of resources and material losses (ISO, 2011). In MFCA, material losses are considered not only in a narrow sense but extend to all utilised materials and economic resources that remain unused and are classified as waste. MFCA includes four cost categories: materials, energy, system, and waste management costs. When applying the MFCA method, material usage is tracked both in physical units and represented in monetary terms. Material flows are calculated within quantity centers, enabling the determination of which portion of materials is incorporated into products and which portion is lost as waste in the form of material losses. Reducing these potential losses can result in energy, cost, and CO_2 emissions savings. Carbon balance management is understood not only as the reduction of CO_2 emissions and other pollutants, but also the minimisation of material losses arising during technological processes. These losses include defective or low-quality products, scrap, waste, damaged items, and expired goods, which exit the company as undesirable residues. Addressing these inefficiencies is critical from both economic and environmental perspectives, as they represent wasted resources and potential environmental harm. Additionally, the MFCA method acknowledges that material waste (losses) can serve as raw material for other technological processes through subsequent recycling and reuse as primary materials. To account for the reuse and recycling of waste, a new quantity center can be created, where new material and energy flows will be evaluated.

Therefore, companies often prioritise decision-making based on cost and production theories, favouring methodologies like MFCA that emphasise resource efficiency, cost savings, and the environmental impact of primary materials and production processes. This targeted approach helps companies streamline resource use and optimise production without incurring the extensive data collection costs of full LCA. Consequently, for many firms, MFCA provides a practical framework for sustainability, supporting corporate decisions in ways that enhance economic and environmental performance while staying aligned with production-focused goals (Schmidt & Nakajima, 2013).

2.2.3 Evaluation of material flow analysis in a sustainable development

Despite the effectiveness of the MFCA, this method has until recently been used in corporate practice only in limited cases to measure actual company costs (Christ & Burritt, 2015; Guenther et al., 2015). The limited adoption of MFCA can partly be attributed to the technical terminology associated with it, such as "quantity centers," "cost categories," or "material distribution keys." These terms often lack parallels in other environmental cost accounting systems, making MFCA challenging to integrate with traditional cost accounting frameworks (Guenther et al., 2017; Nakajima, 2011). Additionally, the method's reliance on matrix and vector calculus poses practical difficulties for some users, complicating its calculations. However, in my assessment, the primary limitation lies in MFCA's perceived lack of a theoretical foundation based on production theory, unlike other cost accounting systems. This absence of a robust theoretical framework has obscured MFCA's role as a reliable system for actual cost accounting. Consequently, understanding the impact of various influencing factors, such as waste, defects, reprocessing, and recycling, on material and product losses has remained challenging. This limitation has also hindered companies' ability to perform differentiated analyses of resource efficiency, thereby restricting MFCA's application for comprehensive resource management and optimisation (Siepelmeyer, 2023).

At the same time, in analysing material flows and resource use within enterprises, significant limitations emerge in traditional financial and economic methods for assessing operational efficiency and material flows. In conventional cost accounting, waste-related expenses are often grouped under broad disposal costs and are then assigned directly to the product. By contrast, MFCA captures all expenses incurred throughout the production chain up to the point at which raw materials become material losses. These hidden costs include expenses related to transportation, machinery use, energy, and auxiliary materials. The cumulative cost of these material losses represents the maximum potential cost savings achievable in an optimally efficient state with no material waste. Another perspective is to view potential cost savings as a budget for investments in waste reduction initiatives. Calculating the actual costs of material losses, companies can significantly enhance their optimisation potential. Moreover, reducing non-essential material and energy flows in production processes can improve energy and resource efficiency while simultaneously reducing overall costs.

Another factor driving the demand for material flow cost accounting in the context of sustainable development is the increasing need for accurate information on the environmental impacts of company activities. Executives are particularly interested in understanding the ecological footprint of waste generated by production processes. Traditional cost accounting methods, which focus primarily on economic objectives, are insufficient to meet these informational needs. These systems often lack the depth required to assess environmental impacts in a comprehensive way.

Consequently, MFCA has seen continuous refinement over recent years, as its application has been shown to reduce material and energy consumption within companies, aligning both financial and environmental objectives. MFCA is especially effective in industries with significant ecological impacts from material losses, such as the metallurgy, oil extraction, mining, and wood processing sectors, as well as in furniture manufacturing (Chompu-inwai et al., 2015; Dunuwila et al., 2018). In these industries, where resource-intensive production generates considerable waste, MFCA provides valuable insights into the flow of materials, enabling companies to identify inefficiencies and reduce their environmental footprint. By minimising resource loss and optimising production, companies in these sectors can achieve both operational cost savings and sustainable practices. This also contributed to the development and improvement of MFCA.

A crucial foundation and requirement for MFCA is a comprehensive model of material and energy flows. This model transparently represents production processes, detailing material and energy inputs, as well as outputs like waste and losses. When implementing MFCA for a production line or an entire facility, the first essential step is always to establish and verify this flow model. Once the material flow model is constructed, efficient and inefficient demands for materials can be forecasted in the budget. These forecasts depend on sales volumes and stock changes, providing valuable insights for environmental accounting systems, such as virtual water calculations or life cycle assessments (Bagliani & Martini, 2012).

Until recently, MFCA has not provided critical information for management, such as the cost implications of material losses or the impact of inefficiencies on product costs. In addition, MFCA is generally developed as a full-cost accounting system without differentiation between variable and fixed costs, limiting its utility in specific corporate decision-making contexts. For sustainable management control, however, companies require detailed projections of both variable and fixed costs to guide decisions, monitor performance, and set sustainability targets effectively.

To address these limitations, recent studies by Dierkes and Siepelmeyer (2019) and Siepelmeyer (2023) propose a theoretical foundation for production and cost accounting within MFCA by developing a differentiated material flow model. This approach aligns with the structure of other cost accounting systems and can be easily integrated into existing cost accounting systems within companies. It also focuses on identifying cost types in various quantity centers, categorising these costs systematically, and developing a well-defined framework for material flow costs and unit cost accounting. The study demonstrates how MFCA can support sustainable development in corporate decision-making to enhance a company's future success. Therefore, further development of this tool is essential, as it provides consistent economic-environmental and economic-social data for managing corporate sustainability effectively.

2.3 Material flows and cost accounting

2.3.1 Classical instruments of cost accounting

Classical cost accounting tools are based on existing methods of financial and economic analysis of enterprise performance and material flows. Specifically, the financial performance of a company is characterised by the availability of financial resources necessary for its normal operations, the effectiveness of their utilisation, the appropriateness of their allocation, financial relationships with other organisations and employees, financial stability, and solvency. The evaluation of financial performance is accompanied by financial analysis, which is typically conducted in accordance with Generally Accepted Accounting Principles (GAAP) or International Financial Reporting Standards (IFRS). These systems are used by organisations to summarise accounting information, disclose supplementary data, and present financial statements, revenues, expenses, and other indicators. GAAP is predominantly used by companies that report their financial results in the United States, whereas IFRS is applied in most other countries.

At the same time, these accounting systems cannot provide company management with comprehensive information for making informed decisions, as cost accounting is a form of managerial accounting aimed at determining the total cost of production by assessing variable costs at each stage of production, as well as fixed costs. Cost accounting does not conform to GAAP and can only be used for internal purposes (Fleischman & Tyson, 1993).

In contrast to financial accounting, which provides information to external users of financial statements, cost accounting does not adhere to established standards and is adaptable to meet managerial requirements. It considers all production expenses associated with manufacturing, including both variable and fixed costs. These costs are first measured and recorded separately, then compared to production results, which helps assess financial performance and make future business decisions. Fixed costs are those that do not change depending on production levels. Typically, these costs include mortgage or rental payments or depreciation. An increase or decrease in production volume will not affect these costs (Fleischman & Tyson, 1993). Variable costs are those tied to the level of production in the company. Operating costs are expenses related to the daily business activities and can be either fixed or variable depending on the specific situation.

One of the key distinctions between cost accounting and financial accounting is how costs are classified. In financial accounting, costs are categorized based on the nature of the transaction, while in cost accounting, they are classified according to the management's informational needs. While cost accounting is frequently used by management for decision-making, financial accounting provides an overview of a company's financial position and performance to external stakeholders through financial statements, detailing revenues, expenses, assets, and liabilities. Cost accounting can be most useful for management when developing budgets and implementing cost control strategies that can increase the company’s net profit in the future.

Cost accounting is an internally focused, company-specific system designed for controlling costs. It offers flexibility and is easy to customise, especially when it comes to cost allocation and inventory valuation. The methods and approaches of cost accounting can differ significantly from firm to firm and can be quite complex. Cost accounting is valuable because it helps determine where a company is spending its resources, how much it is earning, and where losses are occurring. It is focused on reporting, analysing, and improving internal cost control, thereby enhancing efficiency. While cost accounting data cannot be used in financial statements or for tax purposes, it plays critical role for internal control.

There are various cost accounting methods available, each serving a distinct purpose depending on the type of business and its specific needs. According to the Jasinski et al. (2015), the following cost accounting methods are prominent in modern industries: Full Cost Accounting (FCA) and Life Cycle Costing (LCC). FCA provides a comprehensive framework by incorporating both internal and external costs, including environmental and social externalities, allowing for a more holistic assessment of sustainability impacts. LCC extends the focus to the total cost of ownership across the lifecycle of a product, integrating environmental considerations to facilitate long-term decision-making. These methodologies are increasingly applied in industries such as automotive and energy, enhancing the ability of businesses to make informed decisions regarding sustainability and resource efficiency.

One of the best established cost accounting methods is Activity-Based Costing (ABC) (Argyris & Kaplan, 1994; Boons et al., 1992; Boons, 1998; Cooper & Kaplan, 1992; Ness & Cucuzza, 1995) primarily aims to expand the range of cost drivers in product cost calculations in order to broaden the scope of activities for which costs can be causally linked to products. Identifying causal relationships between auxiliary activities and production characteristics creates opportunities for "activity-based planning." Boons (1998) attempts to integrate the benefits of ABC with a more practical model of complex manufacturing processes, aiming to develop a management support system that enhances the control of production performance

The ABC system identifies the overhead costs associated with each activity and allocates them to specific cost objects, such as products or services. It operates on activities, which include any event, unit, or task designed to achieve a specific goal, such as machine setup, production, product design, or finished goods distribution. These activities are also considered cost drivers, and they serve as the basis for allocating overhead costs. Within the framework of ABC, activity analysis is conducted to identify relevant cost drivers. As a result, ABC proves to be significantly more accurate and useful when managers analyse costs and profitability for specific services or products within the company.

While traditional cost accounting systems, have proven to be effective tools for analysing costs and profitability within organisations, the evolving complexity of global business operations and heightened awareness of environmental sustainability have introduced new challenges. Traditional systems, while excellent for internal cost control and operational decision-making, often fall short in addressing the environmental dimension of costs, such as pollution, resource depletion, and waste generation. This growing demand underscores the necessity for accounting frameworks that not only provide insights into operational efficiency but also align with broader sustainability goals. As highlighted by Bebbington and Gray (2001), the integration of environmental considerations into accounting practices represents a critical step toward ensuring that corporate decisions reflect both economic and ecological impacts.

The next chapter explores the demand for additional information about the environmental consequences of corporate activities, addressing how this need has shaped the development of new accounting instruments and frameworks. These innovations aim to bridge the gap between classical cost accounting methods and the growing demand for sustainability-oriented decision-making, emphasising the role of accounting in supporting responsible business practices and contributing to a sustainable future.

2.3.2 Demand for additional information about the environmental consequences of the company's activities

Corporate management increasingly seeks additional information on the ecological consequences of business activities and the integration of environmental cost accounting (Siepelmeyer, 2023). This shift can be attributed to several factors. Firstly, society has become increasingly focused on environmental protection, with growing attention of issues such as the carbon footprint, a measure of the total greenhouse gas emissions directly or indirectly associated with an individual, organisation, event, or product. Many countries have implemented waste recycling programs, reflecting a broader commitment to sustainability. Companies have realised that they can increase their appeal to customers by positioning themselves as environmentally responsible organisations. Secondly, there has been a notable rise in environmental expenditures for some companies, driven by the need to comply with stricter environmental regulations. This raises the need to minimise these costs by adopting more environmentally friendly practices. Consequently, companies that proactively adopt transparent environmental accounting practices are likely to enhance their reputations and gain a competitive edge in the marketplace.

Although providing information on environmental activities is not mandatory in most countries, there is a global trend toward greater transparency and disclosure in this area. Companies employ various formats for disclosing environmental activities, ranging from a single paragraph in their annual reports to dedicated sections that provide detailed insights. The trend has been underscored by the fact that approximately 93% of the top 250 global companies now issue sustainability reports, indicating a significant acceptance and institutionalisation of these practices (Amran & Keat Ooi, 2014). Currently, there is no specific international standard regulating the financial accounting and reporting of environmental expenditures. However, as noted in Chapter 2.1, legislative requirements for environmental reporting have been established at the EU level. The CSRD requires companies to provide comprehensive disclosures on environmental and social issues, underscoring the increasing focus on sustainability. This directive obligates organisations to report detailed information on their environmental and social performance. Alongside this mandatory framework, voluntary guidelines have emerged to enhance reporting quality, such as the Global Reporting Initiative (GRI), UN Global Compact, and The Natural Step, among others. Effective processing and presentation of environmental information require a well-defined classification of expenses and costs associated with such activities, ensuring clarity and consistency in environmental reporting.

Over the past 25 years, a range of theoretical and practical approaches to environmental cost accounting has been developed (Iliopoulou et al., 2024). However, both practitioners and academics continue to debate which methods are most suitable for corporate environmental cost management. This debate has produced varied and sometimes conflicting perspectives on the approaches that best align with the goals of sustainability-oriented businesses.

Research initiatives have introduced several accounting methodologies focusing on the management of material and energy flows. A notable advancement in this field is the VDI Guideline 3800 in Germany, which represents a significant step forward in the development of environmental cost accounting (BMU, 2003). This standard plays a critical role in accurately assessing expenses related to environmental protection measures. This approach improves transparency and accountability in corporate environmental management by enabling comprehensive tracking and analysis of material flows. Internationally, parallel efforts in the United States and Japan have produced frameworks tailored to corporate cost management, although large companies have often developed internal solutions, leaving small and medium-sized enterprises (SMEs) in need of accessible information resources.

In 2001, the United Nations Division for Sustainable Development proposed four managerial accounting methods for identifying and allocating environmental costs (UN, 2001):

1. Input-Output Analysis: this method compares material inputs with product outputs, based on the principle that the total volume of materials entering and exiting a process must be equal. For example, if 100 kg of raw materials were purchased, but only 80 kg of products were produced, the discrepancy of 20 kg must be explained. This difference could consist of 10% sold as scrap and 90% classified as waste.
2. Material Flow Cost Accounting: this method examines not only material flows but also organizational structures, enhancing transparency by analysing the physical volume, costs, and value of material flows. This approach benefits not only the environment but also reduces the overall long-term operational costs of the company.
3. Activity-based Environmental Cost Accounting: this approach allocates internal costs to specific cost centers and cost drivers based on the activities causing these expenses. In environmental accounting, this involves distinguishing between direct environmental costs, attributable to specific joint cost centers, and indirect environmental costs, which are often "hidden" within general overhead expenses. This method provides a more precise allocation of environmental costs, improving cost management and transparency.

4. Life Cycle Environmental Cost Accounting: this method evaluates all environmental impacts and associated costs of producing a particular product throughout its entire lifecycle. It includes all stages, from raw material extraction to production, distribution, use, and end-of-life disposal, providing a comprehensive view of the product's environmental cost footprint.

The informational aspect of environmental management systems serves multiple objectives. Corporations require detailed documentation of their environmental management frameworks, encompassing both internal and external reporting as well as decision-making tools. Environmental accounting plays a key role in this context, as it distinguishes between physical and monetary accounting, which is essential for informed decision-making and accurate reporting. This relationship underscores the connection between environmental accounting and environmental management systems, particularly in alignment with ISO standards. The evolution of material flow cost accounting is a logical progression in this regard. MFCA is a management tool that increases the transparency of material flows and energy consumption in organisations while providing essential information for environmentally responsible decision-making.

As businesses strive to meet the rising expectations for transparency and accountability, the role of environmental accounting will be critical in guiding them towards more sustainable practices. By embracing these methodologies, companies not only fulfil their ethical responsibilities but also position themselves for long-term success in an increasingly eco-conscious market. Publicly funded projects in Germany and Japan demonstrated the effectiveness of MFCA in simultaneously reducing environmental impacts and corporate costs, leading to its eventual incorporation into the ISO 14051 standard in 2011, which solidified its status as a recognised accounting method within the ISO family of standards (Wagner, 2015).

Chapter 3 The design and usefulness of material flow cost accounting

3.1 Overview of approaches for material flow cost accounting

Sustainable development of a company is characterised not only by the achievement of economic goals, but also encompasses the solution of environmental and social problems. Accounting for these factors requires additional information based on the company's activities, which common cost accounting systems cannot provide. Therefore, MFCA has recently gained more attention (Brunner & Rechberger, 2016; Dierkes & Siepelmeyer, 2019; Laner et al., 2014; Siepelmeyer, 2023).

The material flow cost accounting was initially developed in Germany in the early 1980s and has also been extensively adopted in Japan, Southeast Asia, and other industrialised countries. (Bringezu & Moriguchi, 2018; Jasch, 2008; Kokubu & Kitada, 2015; Laner et al., 2014). MFCA is a management tool that helps organisations to better understand the potential environmental and financial impacts of their material and energy practices to achieve environmental and financial improvements (ISO, 2011). In traditional cost accounting, these losses are budgeted as waste costs. By avoiding these material losses, energy, costs and CO_2 emissions can be saved.

Material flow costing distinguishes energy, materials, personnel and all other overheads associated with the waste material as when calculating product-related expenses. With the MFCA method, the cost of material waste includes many more factors than in classical accounting, where waste costs are often treated as disposal costs in the most general way. Material flow cost accounting considers all costs that have been incurred in the process chain before the input material is turned into the final product. These are hidden costs such as transport, machine use, energy, water, and auxiliary and operating materials. A classic example here is the research results of the German scientist Schmidt-Bleek (1998), who drew attention to the fact that for every 1 ton of metallurgical products 50 tons of water are consumed, which, as a rule, remains outside the scope of economic analysis.

Therefore, the MFCA method aims, firstly, to consider all the costs of the process chain and avoid losses in the form of waste, and secondly, to maximise the use of waste in the new process chain of production. The scheme of the MFCA concept is presented in Figure 2 (Hyršlová et al., 2011). In this scheme, all inputs (materials, energy, water and other inputs) and outputs (main products, byproducts, waste, wastewater, emissions) are taken into account. These are defined in the quantity center, where the calculation of material, energy, and costs associated with products and material losses is made.

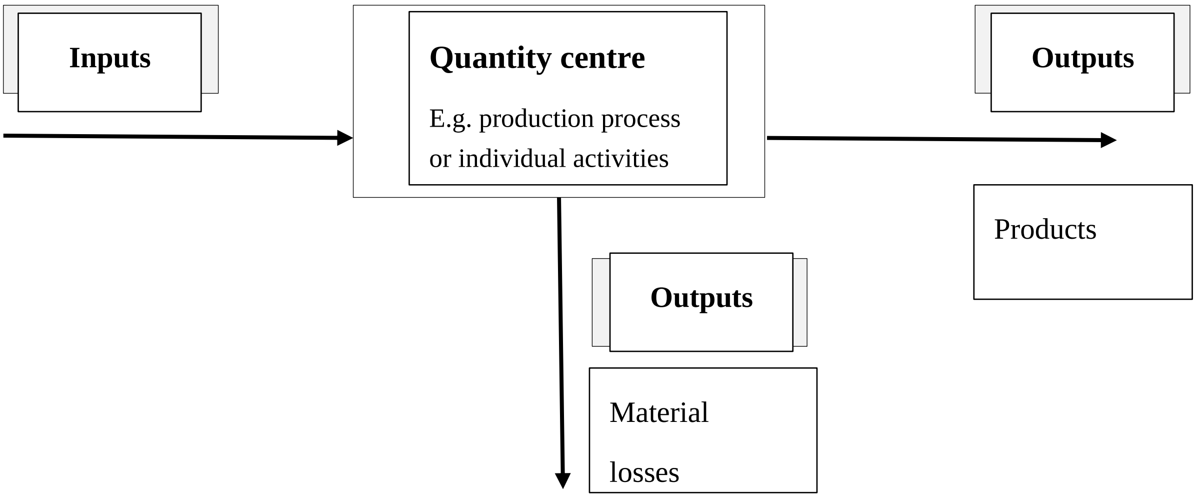


Figure 2. Principle diagram of the MFCA concept. Source: Hyršlová et al. (2011).

The key foundation of material flow cost accounting is a material and energy flow model that clearly illustrates production processes, including resource consumption, waste, and losses. The MFCA concept introduces terminology and definitions including ‘quantity centers’, ‘material flow matrices and vectors’, ‘input and output flows’, etc., which do not exist in in other cost accounting methods (Dierkes & Siepelmeyer, 2019).

A quantity center is a dedicated part of a company or process for which input and output flows are quantified in physical and monetary units (ISO, 2011; Jasch, 2008). In MFCA, it is usually convenient to use matrices and vectors in systems of equations describing material flows. A matrix is a rectangular table of numbers that contains m rows and n columns. In this case, the matrix is said to be of size m by n:

$$A = \begin{pmatrix} a_{1,1} & a_{1,2} & \dots & a_{1,n} \\ a_{2,1} & a_{2,1} & \dots & a_{2,n} \\ \dots & \dots & \dots & \dots \\ a_{m,1} & a_{m,2} & \dots & a_{m,n} \end{pmatrix}$$

In MFCA, a square matrix is often used in calculations, i.e. a matrix with the number of rows equal to the number of columns. A square matrix with ones on the main diagonal and the remaining elements equal to zero is called identity matrix and is denoted by the letter $\underline{E}$.

$$\underline{E} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

A matrix containing one row or one column is called a vector. This is because a vector has coordinates written out in a similar way and its coordinates are read as a row-matrix, for example:

$$\underline{A} = (a_1\ a_2\ \dots\ a_n) \qquad\qquad \underline{B} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix}$$

When working in the MFCA system, it should also be taken into account that the term "output" refers to any product passed to the next stage of production (quantity center) as input and/or output from the enterprise as a final product. From an MFCA perspective, the term "material losses" is not only considered in a narrow sense, but it refers to all invested materials, energy and other economic resources that have not been converted into products and remain unused as waste.

Thus, MFCA focuses on material flows and their associated costs. The system not only provides data in physical units, but also shows the costs of individual material flows. Material costs are a key aspect of material flow costing and serve as a significant expense in manufacturing companies. Material utilisation is tracked in physical units and displayed in monetary units (material costs) within MFCA. Material flows are reconstructed in a quantity center and data is collected to determine what proportion of materials go to production and what proportion go to making products, and what proportion of materials are accounted as material losses.

The MFCA also tracks energy costs, including all energy sources used within the respective quantity center. In addition, system costs are allocated between products and material losses. These costs refer to all costs that are incurred in the processing of material flows in a company, such as personnel costs, depreciation, and other related costs. Every material flow in a company can be considered as a carrier of system costs - regardless of whether it is raw materials, work in progress, products or material losses. System costs are always allocated to output flows and are transferred to downstream flows and material inventories (Hyršlová et al., 2011). Material losses that leave the quantity center are attributed to waste disposal costs. As a result, MFCA is a new accounting method that provides company management with new data that can be used to make management decisions (Wagner, 2006).

In addition, MFCA refers to important environmental cost accounting methods and, using MFCA data, it is possible to propose measures that can lead to improved efficiency of production processes. At the same time, it is also necessary to consider that corporate environmental costs are not only the costs of environmental protection, but also real material and energy flows (Burritt et al., 2002). Then environmental costs can be described as the total of all expenses directly or indirectly related to the consumption of materials and energy, as well as the resulting environmental impact.

Basic requirement for material flow cost accounting is a material and energy flow model, which depends on the problem to be solved. For example, Boons (1998) proposes a production process model as the basis for integrating new cost calculation models into activity-based costing cost accounting. A two-stage procedure is proposed to calculate unit costs for each process. In the first step, the primary resource costs are determined by multiplying the resource consumption for each process j by the corresponding input prices $\boldsymbol{IP_i}$. Accordingly, the primary product costs $\boldsymbol{PC_j}$ can be calculated as:

$$PC_j = \sum_{i=1}^{m} b_{i,j}\, IP_i$$

The second step determines the cost of consumption of internal provided products, which can be determined by the formula:

$$PCP_j = PC_j + \sum_{i=1}^{n} a_{i,j}\, PCP_i$$

where PCP_j – the product cost for each process;

PC_j – the primary cost per product;

PCP_i – the costs of internally provided products;

a_{ij} – the constant and independent values.

As can be seen from the last formula, the cost of PCP_j of product j consists of two components: the cost of primary resources PC_j and the costs of internal products PCP_i. The second component of the formula illustrates the interconnection of all processes in the production system: the determination of PCP_j assumes that all other product costs PCP_i and PCP_j itself, are known (Boons, 1998). Since the formula is valid for all products it is possible to compose a complex system of simultaneous equations:

$$P_1 = b_{11} \cdot IP_1 + b_{21} \cdot IP_2 + \ldots + b_{m1} \cdot IP_m + a_{11} \cdot PCP_1 + a_{21} \cdot PCP_2 + \ldots + a_{n1} \cdot P$$

$$P_i = b_{1i} \cdot IP_1 + b_{2i} \cdot IP_2 + \ldots + b_{mi} \cdot IP_m + a_{1i} \cdot PCP_1 + a_{2i} \cdot PCP_2 + \ldots + a_{ni} \cdot PC$$

$$P_n = b_{1n} \cdot IP_1 + b_{2n} \cdot IP_2 + \ldots + b_{mn} \cdot IP_m + a_1 \cdot PCP_1 + a_{2n} \cdot PCP_2 + \ldots + a_{nn} \cdot P$$

In addition to ‘Activity-Based Costing’, alternative costing models were developed. However, unlike MFCA, these methods did not gain widespread adoption. These alternatives, while offering unique perspectives on cost allocation, often lack the detailed focus on environmental and resource flows central to MFCA, which limits their utility in addressing sustainability objectives within material-intensive industries.

3.2 Analysis and discussion of selected concepts

3.2.1 The concept of Dierkes & Siepelmeyer

The most complete generalised analysis of research in the field of material flow cost accounting based on information about the efficiency and inefficiency of material costs is outlined by Dierkes and Siepelmeyer (2019). The authors show that this information enables companies to plan and control material costs more accurately and to improve the efficiency of production processes. It also notes that the huge environmental consequences of material losses in such industries as mining, oil sector, metallurgical production have contributed to the progressive development of MFCA. However, the simultaneous need for a comprehensive account of all material and energy flows in production has served as a stimulus for the progressive development of MFCA.

Therefore, the model of material flows developed by Dierkes & Siepelmeyer on the basis of production and cost theory is of particular interest, because it allows to determine and analyse efficient and inefficient material and energy flows in quantity centers, taking into account the inefficiency factors of waste and scrap. The authors also present a differentiated material flow model, distinguishing it from other systems of traditional cost accounting. Differentiated material flow involves separating costs into variable and fixed costs by analysing them, and further subdividing costs into efficient and inefficient components. In doing so, the authors propose a novel methodology for calculating all components using the differentiated material flow model. The division of costs into efficient and inefficient is determined by their functions in the quantity center. Inefficient costs are aimed at waste processing and disposal of material losses in the quantity center, while efficient costs are aimed at transforming input data into output data in the quantity center and can be differentiated by cost categories into material costs, energy costs and system costs. The proposed model allows to analyse material and energy flows at the level of quantity centers and units of production in complex production processes, as well as to determine their relationship with inefficiency factors. Describing the division of efficient and inefficient costs into variable and fixed components, the authors reveal the possibility of determining useful information for management accounting in the marginal cost system, which makes it possible to determine the efficient and inefficient demand for materials. An important feature of the developed material flow model is the ability to easily integrate MFCA into other cost accounting systems.

In this material flow model, the company's production area is divided into J quantity centers with j as the quantity center index $j = 1, \dots, J$. $m = 1, \dots, M$ specifies the range for m, where m corresponds to the different types of materials in the system. M represents the total number of materials. $M + J$ refers to an intermediate or final product that results after being processed through the production stages (quantity centers).

Material and product requirements without inefficiencies are denoted r'_m and r'_{M+J}, and, taking into account the work of Boons (1998), are calculated as follows:

$$r'_m = a'_{m,1} \cdot r'_1 + \cdots + a'_{m,M} \cdot r'_M + a'_{m,M+1} \cdot r'_{M+1} + \cdots + a'_{m,M+J} \cdot r'_{M+J} + xa_m + \Delta I_m$$

$$\text{with } m = 1, \dots, M \quad (1)$$

$$r'_{M+J} = a'_{M+j,1} \cdot r'_1 + \cdots + a'_{M+j,M} \cdot r'_M + a'_{M+j,M+1} \cdot r'_{M+1} + \cdots + a'_{M+J,M+J} \cdot r'_{M+J} + xa_{M+J} + \Delta I_{M+J}$$

$$\text{with } j = 1, \dots, J \quad (2)$$

The prime symbol ($'$) represents an ideal or efficient production coefficient without accounting for inefficiencies (like waste or rejects).

First equation balances the material requirements between quantity centers in a production process and external factors like sales and inventory. r'_m is the total material demand (or requirement) for each material m (e.g., $m = 1, \dots, M$). It includes both direct material input and material requirements flowing between different production stages (quantity centers). $r'_1, \dots, r'_M$ represent raw materials or products that feed directly into the system. $r'_{M+1}, \dots, r'_{M+J}$ are outputs or intermediate products produced by the quantity centers $j = 1, \dots, J$. The indices $M + 1$ to $M + J$ specifically label the intermediate products created by the quantity centers. For example, r'_{M+1} represents the total quantity of the intermediate product generated by quantity center 1($j = 1$). The second intermediate product (or another output) would be r'_{M+2}, and so on, up to $M + J$. $a'_{m,M}$ for $m = 1, \dots, M$ is the production coefficient for material m used in quantity center j. It represents the material usage: amount of material m required to produce one unit of output in quantity center j.

$a'_{m,M+1}$ to $a'_{m,M+J}$ are the production coefficients related to the intermediate products in other quantity centers. These intermediate products are outputs from previous quantity centers that serve as outputs from previous quantity centers. Terms $a'_{m,M+1} \cdot r'_{M+1}, \cdots, a'_{m,M+J} \cdot r'_{M+J}$ capture the material flows between intermediate stages in the production process. xa_m represents the external material demand for material m, which depends on the sales volume of final products. The term links the material demand directly to the quantity of goods sold or produced. ΔI_m represents the change in inventory for material m. Positive ΔI_m indicates an increase in inventory (stockpiling), while negative ΔI_m reflects a decrease in inventory (consumption).

Second equation calculates the total efficient gross internal demand r'_{M+J} for intermediate products $M+J$ produced at quantity center j. $a'_{M+j,1}, \dots, a'_{M+j,M}$ represent the production coefficient for raw material M used to produce one unit of the intermediate product $M+J$. $a'_{M+j,M+1}, \dots, a'_{M+J,M+J}$ are the production coefficients for other intermediate products $M+1$ to $M+J$. Each coefficient represents the number of inputs from other quantity centers needed to produce one unit of intermediate product $M+J$. xa_{M+J} represents the total external demand for intermediate product $M+J$, where x is the sales volume and a_{M+J} is the per-unit requirement of that product. ΔI_{M+J} represents the change in inventory for the intermediate product $M+J$ produced by quantity center j, respectively.

It should be noted that the production coefficients $a'_{m,M}$ and $a'_{M+j,M}$ in these equations are the so-called capacity resource consumption factors, which should determine the consumption constraints of resources – either available or provided (Cooper & Kaplan, 1992). For planning purposes, resources are divided into "utilisation resources" and "capacity resources". Utilisation resources can be obtained as needed (e.g. raw materials, supplies, energy, etc.). These resources are typically variable in nature and directly proportional to the level of production output. Capacity resources are allocated resources for actual use (e.g., buildings, equipment, personnel). Unlike utilisation resources, capacity resources often have fixed constraints and do not scale linearly with production. While the consumption of capacity resources, measured in physical units, may be strictly proportional to the volume of output produced, the associated cash flows are not necessarily proportional due to fixed costs, depreciation, or other non-variable expenses. Since in most cases these costs are unknown prior to the calculations, the costs associated with capacity resources and the corresponding consumption factors are assumed to be zero in material and energy flow models. Consequently, these models prioritise the analysis of utilisation resources, which can be directly measured and quantified.

Furthermore, in the context of material flow cost accounting, the coefficients $a'_{m,M}$ and $a'_{M+j,M}$ are set to zero because raw materials do not consume other materials or themselves to exist. In MFCA systems, raw materials ($m = 1, \dots, M$) are inputs supplied externally, not products generated within the system. Thus, $a'_{m,M} = 0$ reflects the logical impossibility of a material consuming itself, while $a'_{M+j,M}$ means that the M-th material is not involved in the production processes of intermediate products. This approach aligns with the broader principles of MFCA, where production relationships are designed to capture only meaningful flows of resources and energy. By setting $a'_{m,M}$ and $a'_{M+j,M}$ to zero, the model effectively excludes non-existent or irrelevant resource flows, ensuring a clear and logical representation of the production system.

However, to obtain a symmetrical system of equations, these variables are included in equations (1) and (2). In order to avoid a large number of "circular" calculations and to simplify product planning and costing in MFCA, a matrix method is used for calculations. Therefore, the presented system of equations (1,2) can be transformed to matrices where $\underline{r'}$ denotes the vector of desired quantities of materials and products, $\underline{A'}$ denotes the matrix of production coefficients, xa denotes the vector of product realisation, and $\underline{\Delta I}$ denotes the vector of inventory changes:

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

This expression can be simplified as follows:

$$\underline{r'} - \underline{A'} \cdot \underline{r'} = \underline{xa} + \underline{\Delta I} \quad \rightarrow \quad \underline{r'} \cdot (1 - \underline{A'}) = \underline{xa} + \underline{\Delta I} \qquad (3.1 \ \& \ 3.2)$$

Replacing 1 by the identity matrix E, the matrix of internal demand coefficients B' is obtained:

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

As a result, the total internal demand for products and materials without inefficiencies can be determined based on the obtained dependencies.

These calculations are made without considering inefficiencies, i.e. rejects and waste, but it should be taken into account that in any production, scrap inevitably appears, and waste is generated. Therefore, to account for the part of production from the quantity center that does not meet the predetermined quality standard and is considered as material losses (rejects), a reject ratio is established by making adjustments to the production coefficients that take the said losses into account.

The reject rate is denoted by β_{M+j}. Then the output and defect of the quantity center will be accounted for by the following expressions:

$$(1 - \beta_{M+j}) \cdot r'_{M+j} \qquad \text{and} \qquad \beta_{M+j} \cdot r'_{M+j}$$

Waste is accounted for by adjusting the production factors $a'_{m,M+j}$ and $a'_{M+k,M+j}$, which, as adjusted, are as follows: $a_{m,M+j}$ and $a_{M+k,M+j}$. After refining the production coefficients associated with waste, the system of equations (1, 2) is refined to determine the total internal demand including inefficiencies. Then, like the original equations (1, 2), the new system of equations is transformed to matrices, where $\underline{A}$ is the matrix with the adjusted production factors, and the matrix of reject rates is denoted by the letter $\underline{W}$. As a result, the vector of gross quantities of materials and products with scrap and waste $\underline{r}$ and the matrix of adjusted total demand coefficients B can be calculated by the following formula similar to the previous calculation:

$$\underline{r} = (\underline{E} - (\underline{A} + \underline{W}))^{-1} \cdot (\underline{xa} + \underline{\Delta I}) = \underline{B} \cdot (\underline{xa} + \underline{\Delta I}) \quad (5)$$

The use of material flow model with waste and rejects allows to determine effective and ineffective material requirements at the level of quantity center and unit of production. This allows material costs to be planned based on the company's sales volume and changes in inventory. In addition, accounting for inefficiencies, including waste and scrap, allows you to determine the total material losses in the production process.

Based on information about material cost efficiencies and inefficiencies, companies can analyse and optimise production processes to reduce waste and improve material efficiency. These steps help companies plan and control material costs more accurately and improve the efficiency of production processes.

The material flow model for a production process with two materials and two products, including the relationship between materials, products, sales, inventory changes and scrap is shown in the diagram (Fig. 3) developed by Dierkes and Siepelmeyer (2019).

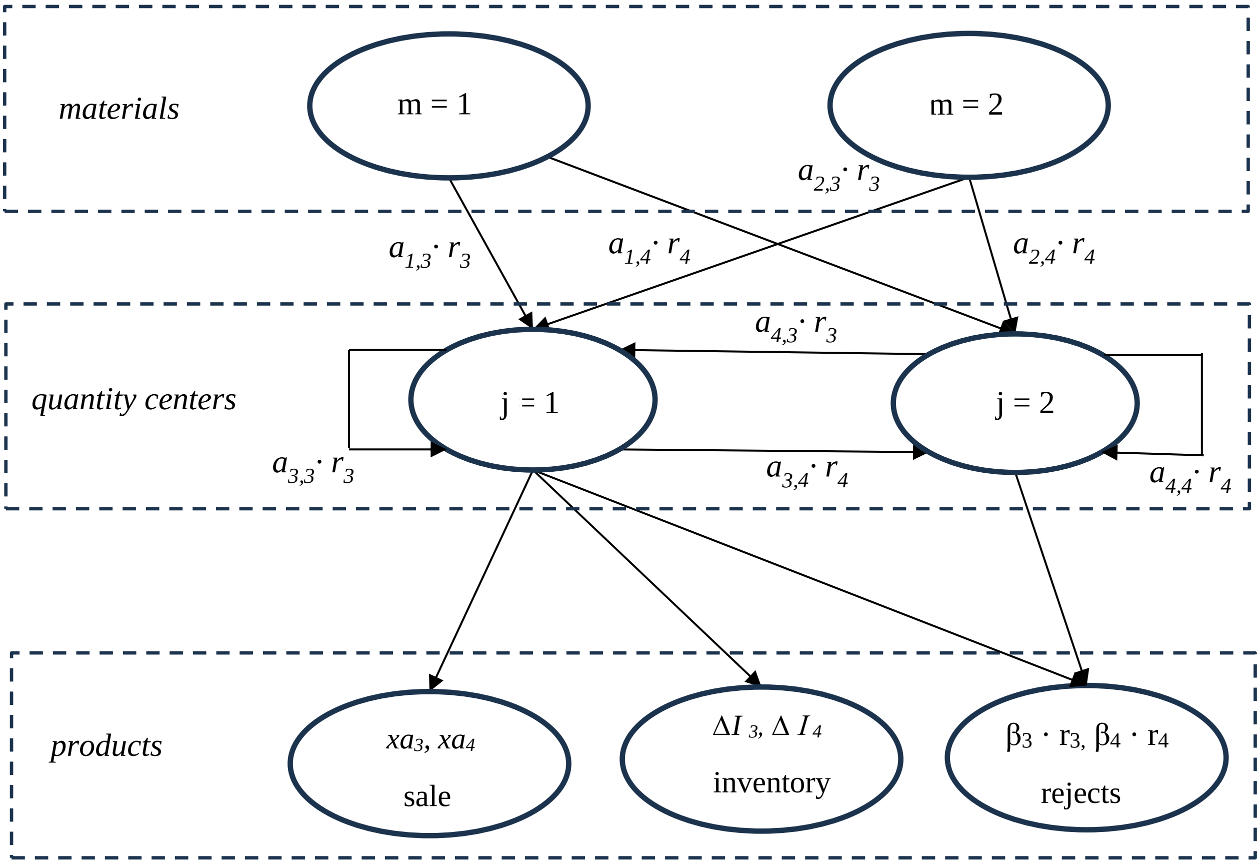


Figure 3. Material flow model with two materials, quantity centers and products. Source: Dierkes & Siepelmeyer (2019).

In this model there are 2 quantity centers. There centers process materials m and transform them into products. Material flows into and out of these centers are tracked.

This model can be represented as a system of equations, that look like:

$$r'_1 = a'_{1,3} \cdot r'_3 + a'_{1,4} \cdot r'_4 + xa_1 + \Delta I_1$$

$$r'_2 = a'_{2,3} \cdot r'_3 + a'_{2,4} \cdot r'_4 + xa_2 + \Delta I_2$$

$$r'_3 = a'_{3,3} \cdot r'_3 + a'_{4,3} \cdot r'_3 + xa_3 + \Delta I_3$$

$$r'_4 = a'_{3,4} \cdot r'_4 + a'_{4,4} \cdot r'_4 + xa_4 + \Delta I_4$$

r'_1 and r'_2 – the total material demand for material $m = 1, 2$

r'_3 and r'_4 – the total output requirements for the products r'_3 and r'_4

$a'_{1,3} \cdot r'_3$ and $a'_{2,3} \cdot r'_3$ – material $m = 1$ and $m = 2$ inputs for quantity center j = 1, ($a'_{m,M+1}$)

$a'_{1,4} \cdot r'_4$ and $a'_{2,4} \cdot r'_4$ – material $m = 1$ and $m = 2$ inputs for quantity center j = 2, ($a'_{m,M+2}$)

$a'_{3,3} \cdot r'_3$ – internal input-output relationship within quantity center j = 1

$a'_{4,3} \cdot r'_3$ and $a'_{3,4} \cdot r'_4$ – flow of intermediate product r'_3 and r'_4 between j = 1 and j = 2

$a'_{4,4} \cdot r'_4$ – internal input-output relationship within quantity center j = 2

xa_1 and xa_2 – external material demand for material $m = 1, 2$

xa_3 and xa_4 – sales of the final products

ΔI_1 and ΔI_2 – change in the inventory for material $m = 1, 2$

ΔI_3 and ΔI_4 – change in the inventory for the products r'_3 and r'_4

As mentioned before, terms like $a'_{m,M}$ or $a'_{M+J,M}$ do not appear in the equations, because it would imply that material m is being used in a self-referencing manner within its own calculation. This does not happen because materials (like $m = 1$ or $m = 2$) are considered inputs into the quantity centers j = 1 and j = 2, not outputs. $a'_{1,2}$ and $a'_{2,2}$ are examples of $a'_{m,M}$ because they represent the input of materials $m = 1$ and $m = 2$ required to produce product $M = 2$. Respectively, $a'_{1,1}$ and $a'_{2,1}$ represent the production coefficient for $m = 1$ and $m = 2$ used to produce product 1. For example, if $a'_{1,1} = 0.8$, this means 0.8 units of $m = 1$ are required to produce one unit of product 1. $a'_{m,M}$ always represents the amount of material m required to produce product M. The term $a'_{M+J,M}$ represents the production coefficient for an intermediate product $M + J$ used to produce a product M. In this case, it would be following production coefficients: $a'_{3,1}, a'_{3,2}, a'_{4,1}$ and $a'_{4,2}$, which are set to zero.

The material loss vector $\underline{v}$ associated with waste and scrap is determined by the difference of vectors $\underline{r}'$ and $\underline{r}$:

$$\underline{v} = \underline{r} - \underline{r}' = (\underline{B} - \underline{B}') \cdot (\underline{xa} + \underline{\Delta I}) \tag{6}$$

Therefore, material losses in any production process can be calculated using internal demand coefficients with or without inefficiencies. The derived relationships were subsequently used to analyse material losses within quantity centers. This analysis considered material requirements, which include both primary and secondary material demand. As a result of the analysis of material distribution in the quantity center, the authors of the paper obtained the dependencies of primary and secondary material demand of the quantity center, which separates effective material demand and ineffective material demand. This approach enables the calculation of the company's total material losses.

Defining effective and ineffective material demand allows for determining the material requirements per unit of production. The effective demand coefficient is determined by dividing the previously determined effective material demand by the quantity center on production volume. Inefficient material demand for products is determined by subtracting the total internal demand coefficient without inefficiency from the total internal demand coefficient with inefficiency. Using the distribution coefficients of quantity center and the total internal demand coefficient inefficiency demand coefficients the authors obtained a relationship establishing the inefficiency material requirements per unit of production.

In general, the structure of MFCA as a complete cost accounting system, obtained by the authors, includes accounting for accounting cost types, as well as accounting by cost centers and accounting by cost units, as shown in Figure 4.

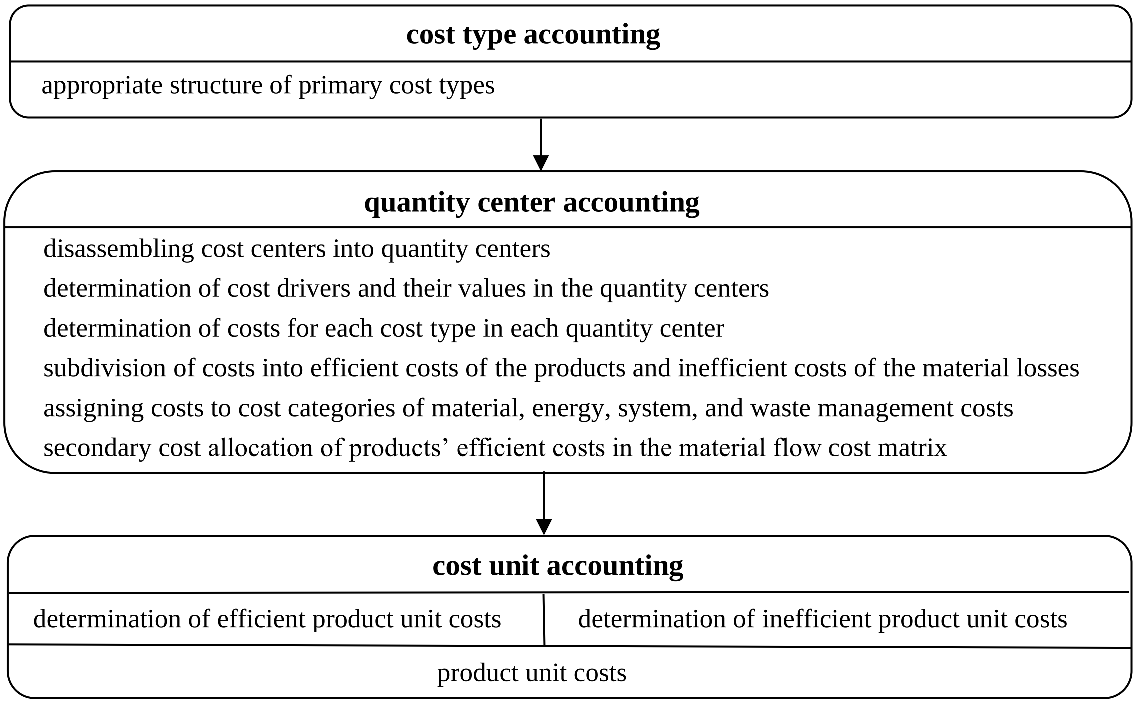


Figure 4. Structure of material flow cost as a full cost accounting system. Source: Dierkes & Siepelmeyer (2019).

Thus, the main points developed by the authors show that the structure of MFCA corresponds to the structure of other cost accounting systems and can be integrated into the relevant cost accounting systems of companies. This opens a wide range of potential applications of MFCA in material flow analysis.

3.2.2 Potential applications in material flow analysis

Although MFCA is based on a material flow model that considers the main inefficiencies of waste and rejects, the potential applications of material flow cost accounting are much broader, and this method can be used as a complete cost accounting system. As shown by Dierkes and Siepelmeyer (2019), the MFCA method can also be used in cost budgeting for material and energy flows, since information about these flows is important for efficient resource utilisation. For this purpose, the authors developed a theoretical production and cost framework for MFCA by developing a differentiated material flow model like known methods used in other cost accounting systems. Theoretical basis allows detailed analysis of material and energy flows in complex production processes and determining their dependence on inefficiencies. However, it must be considered that companies are structured by cost center and the MFCA method is based on quantity center. Therefore, in this case it is assumed that the quantity center is built based on the existing cost center structure.

An important advantage of MFCA is the ability to consider waste and material losses associated with scrap and their distribution across products using variance analysis techniques. Variance analysis is a key element in control and decision-making tools. In a broad sense, this is a discrepancy analysis methodology that involves comparing actual performance against planned targets or standards to identify critical deviations. Based on these deviations, decisions are made to adjust plans, revise performance indicators, reassess employee incentives, and, in some cases, even reevaluate the company's overall strategy.

These capabilities of MFCA enable making the right management decisions within the framework of marginal cost accounting system. It is shown (Bagliani & Martini, 2012; Guenther et al., 2015), that this material flow accounting system can be connected to other environmental accounting systems such as virtual water accounting or carbon footprint accounting. In addition, factors such as waste recycling and production intensity can also be accounted for in the material flow model. In the future, the MFCA method can also be used to incorporate all possible environmental impacts occurring throughout the product life cycle into the cost of a product.

In addition, to save material losses, there is a closer co-operation between suppliers and buyers, which reduces material losses not only for the individual company, but also to reduce possible losses that occur in the entire supply chain. Based on MFCA, environmental management tools that measure inputs and outputs are also developed (Byrne & O'Regan, 2016). For example, the works of Ho et al. (2021) and Schaltegger & Zvezdov (2015) show the effectiveness of MFCA application in wastewater treatment (WWT). WWT is a mandatory process to ensure that the quality of wastewater meets the legal requirements and to reduce the environmental impact. There are many wastewater treatment technologies available on the market and the selection of such technologies is usually based on heuristics (Ho et al., 2021). However, technologies selected using heuristics may not guarantee optimal economic performance. Therefore, it is important for manufacturing companies to develop WWT technology that minimises investment costs while meeting the legal requirements. Most manufacturing companies encounter challenges in achieving this objective, which has become attainable through the implementation of the MFCA method.

The application of material flow cost accounting has been notably prominent in Japan (Environmental Industries Office, 2010). An example of a successful application of the MFCA method is the Canon Group, which started implementing MFCA at all its workplaces since 2004 in combination with workplace-oriented environmental and ecological safety measures (Nakajima, 2006). This comprehensive approach has enabled the organisation to clearly identify processes with the most significant losses. Using this information, Canon Group has been able to reduce waste generation by 40%

The paper by Walz and Guenther (2020) examines the practical impacts of MFCA on companies and its relevance within the framework of industrial ecology. Drawing on evidence from 73 case studies, the study illustrates how MFCA can serve as a powerful tool for enhancing both economic and environmental performance. Specifically, MFCA enables companies to uncover hidden costs associated with waste and inefficiencies, potentially leading to cost reductions of up to 30% in targeted processes and substantial decreases in material losses.

Despite its benefits, the adoption of MFCA remains limited, with only a few hundred companies having fully integrated it into their management control systems globally. The findings underscore that MFCA not only improves transparency in resource flows but also fosters a shift towards a more sustainable operational culture by raising awareness of environmental impacts within organisations. These insights suggest that while MFCA holds significant potential for aligning cost management with environmental stewardship, broader adoption will require addressing existing barriers to integration within conventional management systems.

In my opinion, the greatest efficiency of the MFCA method can be achieved in material-intensive industries related to the development of minerals: mining, oil and gas extraction, metallurgical production, heat, and power engineering, since it is in these industries that the greatest amount of waste is generated, which are raw materials for various industries. At the same time, the operation of enterprises in these sectors has the greatest environmental impact. Based on the MFCA scheme shown in Figure 2 and using the results defined in Section 3.2.1, it can be considered that waste and rejects are the basis for the creation of new quantity center.

As a result, the vector of material losses v associated with waste and scrap will not look unambiguous, since waste and scrap in these new quantity centers will be input materials for new technological processes. For example, wastes of mining and metallurgical plants, which cause significant harm to the environment, contain a significant number of valuable materials that can be obtained after the creation of new quantity center, and the feasibility of their creation is justified based on the analysis of their material and energy flows.

Given the potential for improving the MFCA method, it can be assumed that the application of this method is much wider. For example, in my opinion, based on the analysis of the history of the company's development or improvement of the analysed process, there is a possibility to use this method to justify the prediction of trends in the development of the company, to identify new characteristics of processes by analogy with the Hurst index (Sutcliffe et al., 2016).

In addition, it should be taken into account that the sustainable development of a company is characterised not only by the achievement of economic goals, but also encompasses the solution of environmental and social problems. Since the MFCA method includes the solution of economic and environmental problems of the company, it would be a logical consequence to consider the use of this method in solving social problems as well, since these problems can also be represented by analogy with the Human Development Index. This index is calculated to compare and measure living standards, literacy, education, and longevity. For this purpose, a generalised system of indicators describing quantitative and qualitative characteristics of socio-economic differentiation of social development has been developed and scientifically substantiated. Similar indicators can be defined for a particular company to solve social issues, in my opinion, it is best to use work-life balance (Guest, 2002), i.e. a method that determines the balance required by a working person between the time allocated for work and other aspects of life. Of course, powerful software is needed to develop such programs using the MFCA method, but simultaneously addressing the company's economic, environmental and social problems will allow it to dramatically advance its development and eliminate possible social conflicts.

3.2.3 Critical discussion

When using the MFCA method of material flow cost accounting, matrices and vectors are used for calculations, which has its own peculiarities. When calculating the need for materials and products r'_m and r'_{M+j} in the formulas (1, 2) it is necessary that all the components of the formula were brought to the same dimensions, because the use of different dimensions leads to errors in calculations. Since the MFCA method considers not only material flows but also energy flows - which in turn can be attributed to fixed and variable costs, including electricity, water, heating and other types of costs. All of them have different dimensions (kWh, m^3, Gcal), but can be brought to a single unit of measurement, for example, to a ton of oil equivalent (toe). However, the easiest way is to convert to monetary units (euro), which leads to positive results in calculations.

As the system of equations can be compactly rewritten in the form of matrices and vectors, it is necessary to ensure that the matrix should be square or symmetric, i.e. the number of rows should be equal to the number of columns. Besides, it is necessary to consider that simultaneous consideration of a large number of materials, for example, the use of matrix of the fifth and higher order considerably complicates calculations. Modern computing technology provides a robust mathematical framework capable of analysing material and energy flows at the level of quantity centers and production units in complex manufacturing processes, as well as identifying their relationship to inefficiencies caused by waste and scrap.

At the same time, several literature sources noted that MFCA has had limited application and that the reasons for its limited application in contrast to the commonly used cost accounting systems are the use of different terminology and the absence of some basic elements of common accounting systems such as unit costing. It was also noted that MFCA has been used in practice as a tool for analysing current costs rather than as a planning tool.

However, the concept of Dierkes & Siepelmeyer (2019) convincingly shows that the existing limitations can be successfully resolved, and MFCA can be used not only as a planning tool for any production process, but also as a basis for calculating the full cost of budget cost accounting. Simultaneously, the use of the matrix model not only simplifies the calculations, but also allows connection to other accounting models.

In my opinion, the use of the MFCA method is not limited to planning the company's costs but can also be used for forecasting the company's work, as well as having the potential to facilitate the whole complex of economic, environmental and social challenges of the enterprise at the same time. For this purpose, it is necessary to train specialists of relevant specialties and to widely cover this method in specialised literature.

3.3 Example of material flow cost accounting

3.3.1 Calculation of material flow model based on production theory

Following the recommendations of ISO (2011), a fictitious mining enterprise (mine) was chosen as the analysed entity in the thesis, and an overview as well as an analysis of material flows was conducted. Material and energy flows were studied using the example of a figurative coal industry enterprise that mines thermal and coking coal and pumps mine water to the surface. At the same time, the extracted coal (rock mass) does not meet the requirements for coal quality and is sent to a processing plant for enrichment and production of finished coal products. As a result of the enrichment process, the obtained commercial products (enriched coal) are returned to the mine, part of the product is sent for sale, and part goes to the warehouse. Coal processing waste (rock) at the processing plant is transported to dumps or stored in waste heaps. In addition, because of disruption of the mine workings, water accumulates in the mine and to ensure the life of the enterprise and the safe work of miners, water is pumped out of the mine to the surface, which is drained into water sumps, and then into the hydrological network, causing significant damage to the environment. Therefore, mine water, pumped to the surface, is the product on which significant funds are spent. The production and consumption of these products determines the economy of the enterprise, but these products are also sources of environmental consequences and significant material losses.

Using MFCA terminology, there are $J = 2$ quantity centers, each producing products containing up to $M = 3$ materials, i.e., $j = 1, 2$ and $m = 1, 2, 3$. The first quantity center is the mine itself, which extracts thermal and coking coal (rock mass or raw coal) along with pumped mine water. Thermal coal is designated by the index 1 (m = 1), coking coal with index 2 (m = 2) and pumped mine water with index 3 (m = 3). The second quantity center of the mining enterprise, involved in the technological process, is the processing plant, to which the ordinary thermal and coking coal from the mine is sent

According to Dierkes and Siepelmeyer (2019), $\underline{r}'$ denotes the vector of required quantity of materials and products. In our case, in the production of the required number of products (different grades of coal), an intermediate product (mine water) is involved, which is difficult to quantify in terms of the amount of coal mined. Therefore, it is more convenient to calculate the required resources in monetary terms, i.e. by multiplying the amount of required materials by their cost.

As a result, the material cost vector $\underline{r}'$ will consist of primary product costs and internal product costs Dierkes and Siepelmeyer (2019). Accordingly, based on equations (1, 2), in my calculations the material cost vector $\underline{r}'$ will be determined by the costs $a'_{1,1} \cdot r'_1$ for the production of ordinary thermal coal and $a'_{2,1} \cdot r'_2$ of coking coal, and by the costs of their enrichment at the processing plant, which are denoted by $\alpha'_{1,1} \cdot r'_1$ and $\alpha'_{2,1} \cdot r'_2$, respectively. The costs of pumping out mine water are labeled $a'_{3,1} \cdot r'_3$ and the costs of its subsequent mechanical and biological treatment are labelled $a'_{3,2} \cdot r'_3$. The costs of pumping water for the extraction of thermal coal are designated $a'_{1,3} \cdot r'_3$ and, accordingly, for the extraction of coking coal - $a'_{2,3} \cdot r'_3$. At the same time, to ensure technological processes for coal enrichment, water is also sent to the processing plant, which is indicated by costs $\alpha'_{3,1} \cdot r'_3$. The diagram of material and energy flows of the mine is presented in Figure 5. For ease of reading and to avoid overcrowding the diagram, the enriched coal is represented by xa_n and ΔI_n, where n = 1 refers to enriched thermal coal, and n=2 refers to enriched coking coal. In this notation, xa_n denotes the sales volume of the final product (enriched coal), while ΔI_n represents the change in inventory levels for the respective product type.

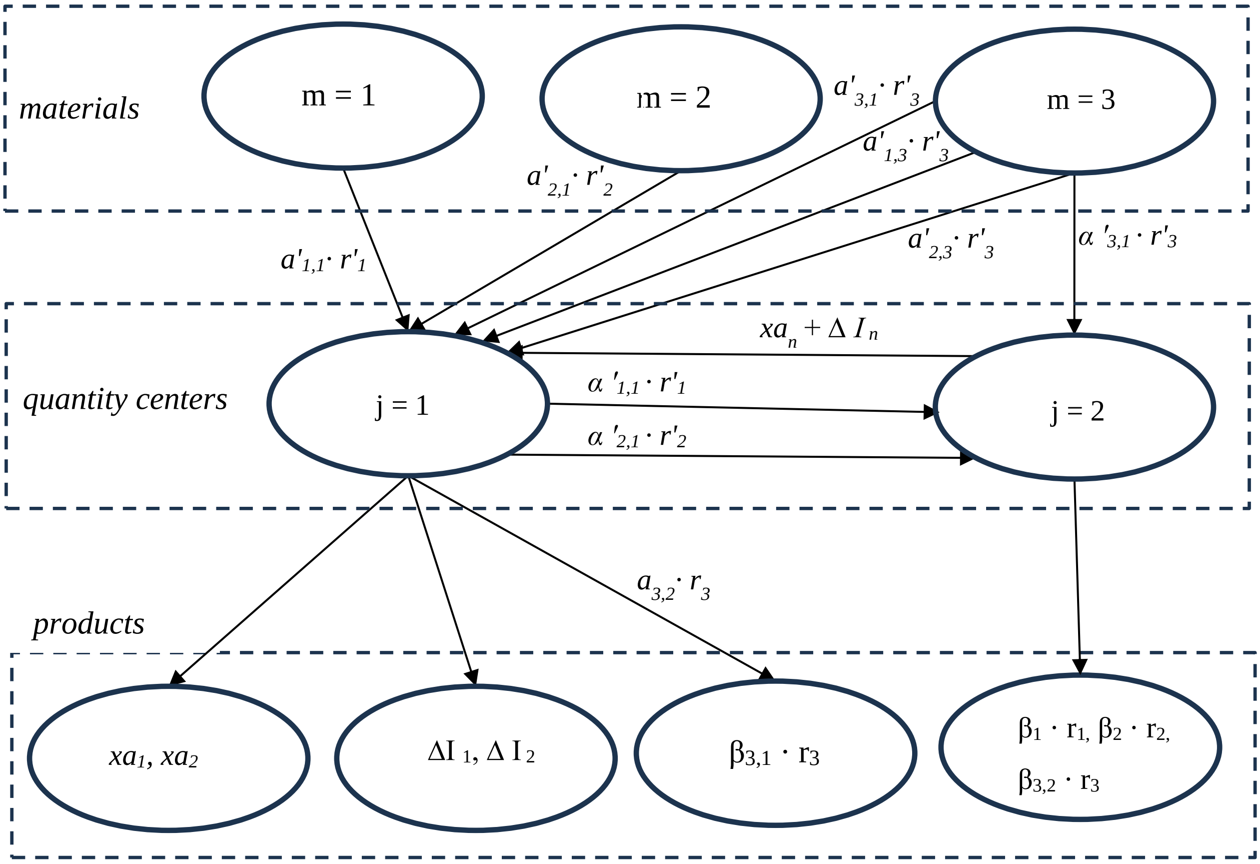


Figure 5. Diagram of material and energy flows of the fictitious mine enterprise.

Using dependencies (1,2), the following system of equations is obtained:

$$r'_1 = a'_{1,1} \cdot r'_1 + a'_{1,3} \cdot r'_3 + \alpha'_{1,1} \cdot r'_1 + xa_1 + \Delta I_1$$
$$r'_2 = a'_{2,1} \cdot r'_2 + a'_{2,3} \cdot r'_3 + \alpha'_{2,1} \cdot r'_2 + xa_2 + \Delta I_2 \quad (7)$$
$$r'_3 = a'_{3,1} \cdot r'_3 + a'_{3,2} \cdot r'_3 + \alpha'_{3,1} \cdot r'_3 + xa_3 + \Delta I_3$$

where xa_1 and xa_2 are the sales volumes of finished coal products, thermal and coking coal, respectively, and ΔI_1 and ΔI_2 are the change in product inventories in the warehouse. xa_3 and ΔI_3 is an intermediate product that is not sold and therefore equals zero in this equation.

The resulting system of equations can be compactly rewritten in the form of matrices and vectors. The notation A' is used to denote the required quantity of the matrix of production coefficients:

$$A' = \begin{matrix} a'_{1,1} + a'_{1,3} + \alpha'_{1,1} \\ a'_{2,1} + a'_{2,3} + \alpha'_{2,1} \\ a'_{3,1} + a'_{3,2} + \alpha'_{3,1} \end{matrix} \quad (8)$$

Considering that the sales volumes xa are equal to the sum of the sales volumes of thermal and coking coals ($xa = xa_1 + xa_2$), and the coal reserves in the warehouse are equal to the sum of the reserves of each type of coal ($\Delta I = \Delta I_1 + \Delta I_2$), the result can be stated as depicted in formula (3).

Thus, the total demand for thermal and coking coal and the amount of mine water pumped, excluding scrap and waste, can be calculated using formula (6). The waste that arises from the mining operation and the possible use of mine water pumped to the day surface will be considered additionally. To determine the needs for thermal and coking coals, calculations will be conducted on the example of a fictitious mine enterprise. This involves utilising production coefficients, sales volumes, and the coal reserves in the warehouse (which account for 10% of the sales volume). The values of production coefficients and sales volumes are displayed in Table 1.

Table 1. The values of production coefficients and sales volumes for enterprise

Variable	*Value*
$a'_{1,1}$	5
$a'_{1,3}$	2
$\alpha'_{1,1}$	1
$a'_{2,1}$	3
$a'_{2,3}$	3
$\alpha'_{2,1}$	2
$a'_{3,1}$	1
$a'_{3,2}$	0,25
$\alpha'_{3,1}$	1,25
xa_1	600,00
xa_2	400,00
xa_3	0,00
ΔI_1	60,00
ΔI_2	40,00
ΔI_3	0,00

Following, an example of calculating the gross quantity of materials and products excluding rejects and waste. Taking formula (4) into account, results in the following equation:

$$\left(\underline{E} - \underline{A}'\right) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} a'_{1,1} & a'_{1,3} & \alpha'_{1,1} \\ a'_{2,1} & a'_{2,3} & \alpha'_{2,1} \\ a'_{3,1} & a'_{3,2} & \alpha'_{3,1} \end{pmatrix}$$

or, substituting the determined values of production coefficients:

$$(\underline{E} - \underline{A}') = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 5 & 2 & 1 \\ 3 & 3 & 2 \\ 1 & 0{,}25 & 1{,}25 \end{pmatrix} = \begin{pmatrix} -4 & -2 & -1 \\ -3 & -2 & -2 \\ -1 & -0{,}25 & -0{,}25 \end{pmatrix}$$

The inverse matrix (E - A') will be equal to:

$$(\underline{E} - \underline{A}')^{-1} = \underline{B}' = \begin{pmatrix} 0 & 0{,}2 & -1{,}6 \\ -1 & 0 & 4 \\ 1 & -0.8 & -1{,}6 \end{pmatrix} \qquad det\, B' = |0{,}8|$$

$$\underline{r}' = (\underline{E} - \underline{A}')^{-1} \cdot (\underline{xa} + \underline{\Delta I}) = \underline{B}' \cdot (\underline{xa} + \underline{\Delta I}) = 0{,}8 \cdot (\underline{xa} + \underline{\Delta I}) \qquad (9)$$

Considering the data of Table 1, the sum of vectors xa and ΔI will be equal:

xa = xa_1 *(600; 0; 0)* + xa_2 *(400; 0; 0)* + xa_3 *(0; 0; 0) = (1000; 0; 0);*

ΔI = ΔI_1*(60; 0; 0)* + ΔI_2 *(40; 0; 0)* + ΔI_3 *(0; 0; 0) = (100; 0; 0).*

where $\underline{r}'$ *= 0,8 ·* $(\underline{xa} + \underline{\Delta I})$ *= 0,8 · (1100; 0; 0) = (880; 0; 0).*

Since the value of the determinant of the matrix is less than one (0.8), it indicates that the sales volume of coal exceeds the costs of its production, and the enterprise operates at a profit. Based on formula (4), internal demand for materials and products can be calculated without any inefficiencies.

When analysing material flows of a mining enterprise, defects in mining the coal, are generally negligible, however, as a result of a decrease in the thickness of the coal seam (reduction in its height) or incorrectly selected equipment, the amount of rock removed along with coal may increase. As a result, the amount of rock requiring separation from coal increases at the processing plant (the second quantity center), resulting in decreased coal products, and an increase waste. Therefore, losses due to inefficiency have to be accounted for by adjusting the production coefficients $\alpha'_{1,1}$, $\alpha'_{2,1}$ and $\alpha'_{3,1}$.

That is, the production coefficients should be adjusted only in the 2nd quantity center considering the formation of additional waste in the rock mass. Therefore, the costs in the 2nd quantity center related to separation of additional rock from coal should increase. To account for additional costs associated with inefficiency, coefficient $\beta_{m,j}$ is introduced, which for simplification of calculations will be assumed to be the same for both types of products and equal to 10%. The reject rate $\beta_{m,j}$ represents the percentage of products from the quantity center 2 that do not meet the predetermined quality standard and is considered as material loss (Dierkes et al., 2016). Thus, the product yield and the amount of waste generated in the second quantity center can be calculated by multiplying by the corresponding coefficient $\beta_{m,j}$.

In this case the system of equations (8) will have the following form:

$$\begin{aligned}
r'_1 &= a'_{1,1} \cdot r'_1 + a'_{1,3} \cdot r'_3 + \alpha'_{1,1} \cdot r'_1 + xa_1 + \Delta I_1 + \beta_{1,2} \cdot \alpha'_{1,1} \cdot r'_1 \\
r'_2 &= a'_{2,1} \cdot r'_2 + a'_{2,3} \cdot r'_3 + \alpha'_{2,1} \cdot r'_2 + xa_2 + \Delta I_2 + \beta_{1,2} \cdot \alpha'_{1,1} \cdot r'_1 \\
r'_3 &= a'_{3,1} \cdot r'_3 + a'_{3,2} \cdot r'_3 + \alpha'_{3,1} \cdot r'_3 + 0 + 0 + 0 + 0
\end{aligned} \tag{10}$$

According to Dierkes & Siepelmeyer (2019), this system of equations can also be transformed to matrices: where A represents the matrix of adjusted production ratios, and W denotes the matrix of the reject rates, see equation (5).

By substituting the theoretical values of production coefficients and increasing them by 5% (β = 0.05), following matrix is derived:

$$(\underline{E} - \underline{A}') = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 5 & 2 & 0{,}95 \\ 3 & 3 & 1{,}9 \\ 1 & 0{,}25 & 1{,}18 \end{pmatrix} = \begin{pmatrix} -4 & -2 & -0{,}95 \\ -3 & -2 & -1{,}9 \\ -1 & -0{,}25 & -0{,}18 \end{pmatrix}$$

The inverse matrix of $(E - A')$ will be equal to:

$$(\underline{E} - \underline{A}')^{-1} = \underline{B}' = \begin{pmatrix} 46/429 & 49/429 & -760/429 \\ -544/429 & 92/429 & 1900/429 \\ 500/429 & -400/429 & -800/429 \end{pmatrix} \qquad det\, B' = |0{,}93|$$

With β = 10% the following results are obtained:

$$(\underline{E} - \underline{A}') = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 5 & 2 & 0{,}9 \\ 3 & 3 & 1{,}8 \\ 1 & 0{,}25 & 1{,}12 \end{pmatrix} = \begin{pmatrix} -4 & -2 & -0{,}9 \\ -3 & -2 & -1{,}8 \\ -1 & -0{,}25 & -0{,}12 \end{pmatrix}$$

The inverse matrix $(E - A')$ will be equal to:

$$(\underline{E} - \underline{A}')^{-1} = \underline{B}' = \begin{pmatrix} 14/61 & 1/61 & -120/61 \\ -96/61 & 28/61 & 300/61 \\ 250/61 & -200/183 & -400/183 \end{pmatrix} \qquad det\, B' = |1{,}09|$$

As the results clearly depict, even with 10% of inefficiencies, the enterprise's costs for the extraction of ordinary thermal and coking coal, pumping out mine water and the costs of enriching coal at the washing plant exceed sales volumes of coal products. If inefficiencies increase to 30%, the enterprise will operate at a loss and it is necessary to take additional measures to improve the quality of raw coal and reduce the rock content in the mined rock mass, as well as use water more efficiently.

Cost calculation when β = 30%:

$$\left(\underline{E}-\underline{A}'\right)=\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}-\begin{pmatrix}5&2&0{,}7\\3&3&1{,}4\\1&0{,}25&0{,}88\end{pmatrix}=\begin{pmatrix}-4&-2&-0{,}7\\-3&-2&-1{,}4\\-1&-0{,}25&-0{,}12\end{pmatrix}$$

The inverse matrix $(E-A')$ will be equal to:

$$(\underline{E}-\underline{A}')^{-1}=\underline{B}'=\begin{pmatrix}{}^{24}/_{11}&-{}^{17}/_{11}&-{}^{56}/_{11}\\-{}^{71}/_{11}&{}^{48}/_{11}&{}^{140}/_{11}\\{}^{50}/_{11}&-{}^{40}/_{11}&-{}^{80}/_{11}\end{pmatrix}\qquad det\,B'=|3{,}64|$$

Calculation results for different scenarios of coal purity and their impact on the matrix differentiation determinant beta are depicted in Table 2.

Table 2. Change in matrix determinant with increasing rock content in the mined rock mass

Increase in content rocks, %	1,00 %	3,00 %	5,00 %	10,00 %	15,00 %	30,00 %
$det\,B'$	0,84	0,87	0,93	1,09	1,32	3,64

The obtained dependencies allow analysing material flows at the enterprise, as well as analysing the economic situation (Ch. 3.3.2).

3.3.2 Economic situation

Material losses associated with inefficiencies at the mining enterprise are generated in the second quantity center - at the processing plant during the processing of rock mass by separating the rock and obtaining finished coal products. This occurs when some of the products from the first quantity center do not meet a predetermined quality standard and require quality improvement.

The analysis of material losses in the second quantity center is given below. To establish general trends in the impact of changes in the percentage of scrap on the cost of production in the extraction of thermal and coking coal at our conditional enterprise, calculations of determinant matrices were carried out. The results of calculations are presented in following tables.

Table 3. Relationship between determinant values and percentage increase in coking coal content

Increase in content rocks, %	1,00 %	3,00 %	5,00 %	10,00 %	15,00 %	30,00 %
$det\,B'$	0,81	0,84	0,87	0,95	1,05	1,54

Table 4. Relationship between determinant values and percentage increase in thermal coal content

Increase in content rocks, %	1,00 %	3,00 %	5,00 %	10,00 %	15,00 %	30,00 %
$det\,B'$	0,79	0,79	0,76	0,73	0,70	0,62

It should be noted that the influence of coking coal inefficiency has a greater impact on the matrix determinant than thermal coal, which was considered by adopting the values of production coefficients. Final conclusions can be made when analysing the values of the above products.

Whereas water used at the processing plant cannot be considered with inefficiencies, because water has no "rejects", still the calculations of the determinant matrix show, the necessity of reducing water consumption when the production coefficient $\alpha'_{3,1}$ changes, to increase the efficiency of the mining enterprise, as well as to find the possibility of its reuse.

Table 5. Relationship between determinant values and change of the production factor of water used in the processing plant

Production factor $\alpha'_{3,1}$	1,25	1,35	1,4	1,5	2,00	4,00
$det\,B'$	0,8	0,7	0,66	0,58	0,55	0,15

The components of the cost as a result of extraction of planned volumes of thermal coal will be calculated, assuming that the initial data are known from the results of the enterprise (Table 6).

Table 6. Cost and coefficients of the thermal coal

Variable	*Value*
Annual volume of coal production, million ton	0,6
Cost of 1 ton of ordinary thermal coal, €	80
Production coefficient $\alpha'_{1,1}$	5
Cost of pumping water, million €	8,76
Production coefficient $\alpha'_{1,3}$	2
Reject rate $\beta_{1,2}$ in %	5,0
Production coefficient in the enrichment process, $\alpha'_{1,1}$	1
Enrichment costs of 1 ton of raw coal, €	20

r_1 = 5 · 0,6 · 80 + 2 · 8,76 + 1,05 · 1 · 0,6 · 20 = 240 + 17,52 + 12,6 = 270,12 *million* €

To obtain 600 thousand tons (tt) of finished coal products (for the energy industry), fictitious mine incurs costs totalling 270,12 million euros. The majority of these expenses are primary costs of the product, i.e. mining of rock mass. The remaining costs of internal products are associated with pumping out mine water and beneficiation of rock mass at the processing plant. Despite the high price of thermal coal products at 400 euros per 1 ton, the company would operate at a loss in this scenario, extracting only thermal coal:

600 tt · 400 €/ton = 240 *million* €

This loss is attributed to both the high production factor and the significant costs associated with pumping out mine water, as well as the necessity for coal enrichment at the processing plant. Detailed calculations of the cost components arising from the extraction of planned volumes of coking coal will be provided, assuming that the initial data have been derived from the enterprise's operational results (Table 7).

Table 7. Cost and coefficients of the coking coal

Variable	*Value*
Annual volume of coal production, million tons	0,4
Cost of 1 ton of ordinary of coking coal, €	100
Production coefficient $a'_{2,1}$	3
Cost of pumping water, million €	8,76
Production coefficient $a'_{2,3}$	3
Reject rate $\beta_{2,2}$ in %	5
Production coefficient in the enrichment process $\alpha'_{2,1}$	2
Enrichment costs of 1 ton of raw coal, €	20

$r_2 = 3 \cdot 0{,}4 \cdot 100 + 3 \cdot 8{,}76 + 1{,}05 \cdot 2 \cdot 0{,}4 \cdot 20 = 120 + 26{,}28 + 16{,}8 = 163{,}08\ million$ €

Revenues from coking coal sales will be as follows (price of coking coal products at 480 euros per 1 ton):

400 tt · 480 €/ton = 192 $million$ €

In this scenario, the revenues from coking coal sales (192 million €) exceed the costs of mining coking coal by 28.92 million € (192 - 163.08 = 28.92). However, when considering the additional costs associated with thermal coal mining, the company still operates at a loss, which is a common challenge for many coal companies in Europe.

If the enterprise were to eliminate inefficiencies—ensuring that the extracted rock mass meets quality standards—coal enrichment at the processing plant would no longer be necessary, thereby eliminating associated costs and improving financial performance.

Eliminating named inefficiencies, the costs of thermal coal mining and mine water pumping will be:

$r_1 = 5 \cdot 0{,}6 \cdot 80 + 2 \cdot 8{,}76 = 240 + 17{,}52 = 257{,}52\ million$ €

The costs of coking coal mining and mine water pumping will be as follows:

$r_2 = 3 \cdot 0{,}4 \cdot 100 + 3 \cdot 8{,}76 = 120 + 26{,}28 = 146{,}28\ million$ €

As a result, revenues from the sale of coal products (thermal and coking coal) will amount to 28.2 million € and the company will operate efficiently:

192 + 240 – 257,52 – 146,28 = 28,2 (million €).

Thus, the analysis of the economic situation clearly demonstrates that, to ensure the effective operation of the mining enterprise, it is essential to eliminate inefficiency factors or reduce them as much as possible.

By utilising the overall MFCA framework (see Fig. 2), it becomes feasible to design strategies for establishing new quantity centers that not only reduce inefficiency factors but also create opportunities for generating additional profits. An example of inefficiency reduction is depicted in Figure 6.

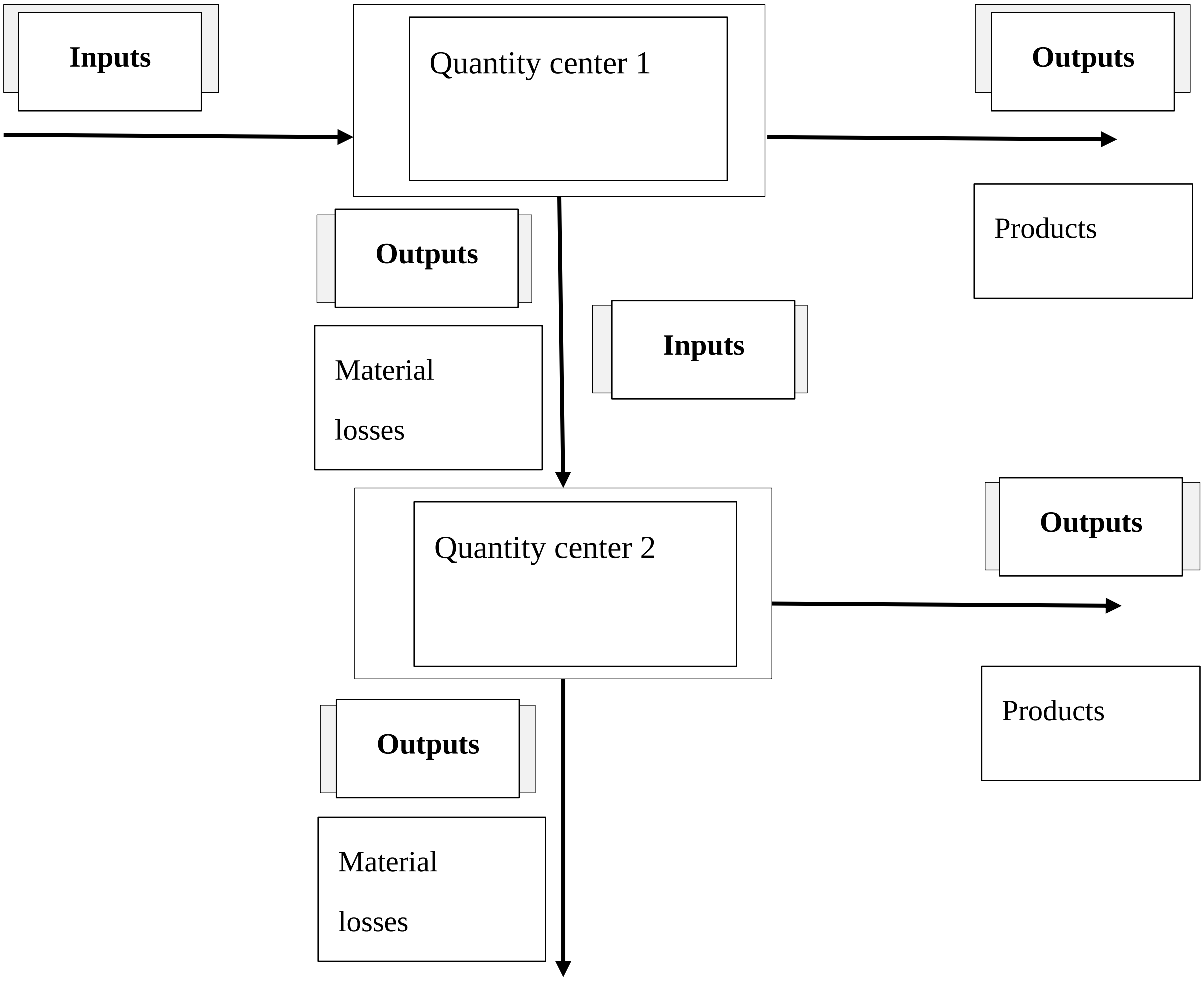


Figure 6. A scheme for reducing inefficiency factors through the utilisation of production waste.

According to this scheme, waste from coal production (mine water) is not discharged into the hydrological network but is directed to heat pump installations for extracting low-potential heat, which can then be utilised for technological purposes. Such approaches are essential in identifying and addressing areas of waste within the production process, thereby optimising resource allocation and enhancing financial performance. The strategic implementation of these schemes can lead to more sustainable operations for organisations adopting the MFCA methodology. Practical recommendations for reducing inefficiencies at a mining enterprise are given in Chapter 3.3.3.

3.3.3 Practical recommendations for reducing inefficiencies at a mining enterprise

Matrix of material flows analysis of the mining enterprise allowed us to identify areas to improve the efficiency of the enterprise. To achieve this, it is crucial to eliminate potential inefficiencies that may occur during operations. In the coal mining industry, such inefficiencies can arise due to changes in mining and geological conditions, leading to an increase in coal ash content (increase in the content of rock in the rock mass). Additionally, selecting inappropriate cleaning equipment, can further elevate the rock content in the extracted rock mass. These inefficiencies result in higher costs at the second quantity center, primarily due to additional coal processing expenses, and contribute to a reduction in the yield of finished coal products. Addressing these inefficiencies is essential for optimizing operational performance and reducing unnecessary expenditures.

As shown by the analysis of the economic situation, another important factor in improving the efficiency of the company is the careful management of water resources, particularly given the rising costs thereof. Furthermore, addressing environmental challenges is essential for the sustainable development of the enterprise. Currently, after undergoing mechanical and biological treatment in settling tanks, mine water is discharged into the local hydrological network, requiring mining companies to pay environmental fines. However, these penalties can potentially be partially or fully offset by leveraging the low-potential energy of mine water, which can generate additional profits for the company.

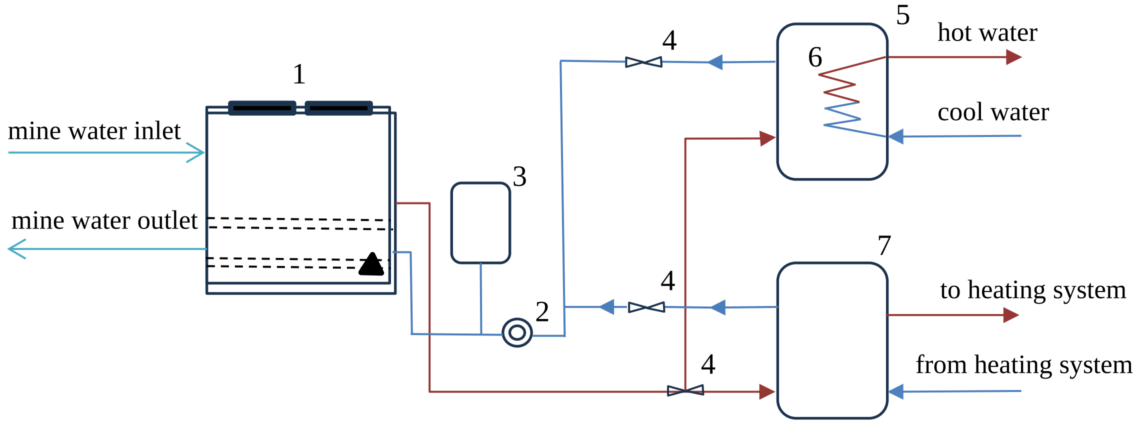
Recent research highlights the potential of abandoned coal mines as significant sources of zero-carbon geothermal energy, a field that has gained notable interest worldwide (Banks et al., 2019; Wang et al., 2024; Zhang et al., 2024). In the United Kingdom, abandoned coal mines have increasingly been adapted for geothermal energy applications to provide low-carbon heating solutions. By investigating sites in the UK, including Markham and Caphouse Collieries, this study provides valuable insights into the performance and practical considerations of geothermal heating systems using mine water, highlighting both the environmental benefits and the engineering challenges associated with these systems (Banks et al., 2019)

In China, the development of geothermal energy from mine water has advanced significantly, with a growing number of publications on the topic. The utilisation of geothermal heat from abandoned coal mines, especially through water-source heat pumps, has become an effective method for low-carbon energy production. The study by Wang et al. (2024) explores the application of geothermal heat recovery systems in a decommissioned mine in Shandong, China. This research highlights the potential of abandoned mine water as a reliable, sustainable energy source that aligns with China's climate goals by reducing fossil fuel dependence and promoting clean heating solutions for building spaces. This approach not only reduces carbon emissions but also revitalises local economies that were affected by coal mine closures.

Zhang et al. (2024) explore the efficiency of water source heat pump systems in abandoned coal mines, examining how different well configurations affect energy output and system stability. Through a series of simulations, the study identifies an arrangement of wells that maximises heating efficiency while preventing heat loss due to temperature shifts in the underground environment. The findings reveal that a specific triangular arrangement of wells delivers the most stable and efficient heating, showing significant energy savings compared to traditional heating methods, such as gas boilers. This research demonstrates that abandoned mines can be repurposed effectively for sustainable building heating, offering a clean energy solution that contributes to China's green energy transition and reduces dependency on fossil fuels (Zhang et al., 2024).

As a heat source, mine water from abandoned mines is a valuable resource that is utilised by drilling boreholes to extract water from the depth. The water is then passed through heat pumps and extractors, which compress and elevate its temperature significantly. This heated water is then transferred to heating networks. After the heat being utilized by nearby buildings, the cooled water can be returned into the mine for reheating. The advantage of mine water heating is that it works all year round. The temperature does not depend on the time of year, and the water can be used not only to heat but also to cool homes.

Considering the significant advantages of utilising mine water from abandoned mines, I applied this logic to water from fictitious mine and use it for heating of the mine's administrative and household complex and buildings of the mine settlement. Let's assume that the mine water of our conditional enterprise is pumped out of the mine at a rate of 100 m^3 /h and has a temperature from +15° to +25 C° (depending on the time of year). For utilisation of low-potential heat of mine water it is offered to direct water after purification filters through pipes to heat receivers of heat pumps according to the following scheme (Fig. 7).



1 - water-to-water heat pump
2 - heat pump
3 - expansion tank
4 - valves
5 - heat accumulator tank of the hot water supply
6 - heat exchanger heater for hot water
7 - heat accumulator tank of the heating system

Figure 7. Technological scheme of heat pumping unit that utilises mine water.

The primary device for heating buildings is a heat pump, which operates by compressing a gaseous refrigerant (such as Freon or ethylene glycol) using a compressor. This compression, driven by electrical energy, increases the refrigerant's pressure and temperature, a process explained by the universal Clapeyron relation, which connects temperature and pressure changes to phase transitions and thermodynamic properties. The heat pump then transfers this generated heat to the building's heating system, making it an efficient solution for temperature regulation.

The heated refrigerant (85ºC) enters the condenser under high pressure. In the condenser, heat is transferred from the heated refrigerant to the heat transfer medium (water). As a result, the refrigerant is cooled, and the condensation process (transition from gaseous to liquid state) takes place. After the condenser there is an expansion valve, the function of which is to reduce the pressure of the refrigerant. As a result of the pressure drop, the temperature also drops. After passing through the expansion valve, the refrigerant enters the heat exchanger, which is located outside (evaporator). In the evaporator the refrigerant vaporises (changes from liquid to gas) or, more simply, boils. The boiling point of the refrigerant is lower than the outside air temperature. During the boiling process, the Freon takes heat from the mine air sent to the heat exchanger and the cycle is repeated. As a result of the heat pump operation, part of the heated water in the secondary circuit goes to the heating system of the building and part is used in the hot water supply system (canteen, laundry, bathhouse).

Extraction of low-potential heat from mine water provides an environmentally friendly method of heating and conditioning. The advantages of this method include:

- High economic efficiency: Each kilowatt of electricity used by the system generates between 2.5 to 4 or more kilowatts of thermal energy, making it highly cost-effective.

- Independence and versatility: Heat pumps do not rely on fossil fuels, enabling their use in diverse climates and locations. A single system can provide heating, cooling, and hot water simultaneously, adding to its utility.

- Environmental safety: Heat pumps for mine water extraction offer a clean heating and cooling method with no harmful emissions such as CO, CO_2, NO_x, SO_2, or PbO_2, ensuring minimal environmental impact.

- Operational safety: The absence of combustible fuels (e.g., gas or diesel) reduces risks associated with fires, explosions, or leaks of hazardous substances, making these systems safe and reliable.

Furthermore, utilising waste from coal mining for heat extraction offers substantial economic benefits by harnessing low-grade heat from pumped mine water. An economic efficiency calculation of this proposed technical solution can be performed using the baseline data of the enterprise.

The proposed heat pump station for hot water supply, utilizing heat from mine water, operates year-round. Prior to its implementation, water heating for heating and technological purposes was carried out using electric boilers during the non-heating season (5,300 hours annually) and a coal-fired boiler during the heating season. The initial data for the calculations and the technical and economic indicators of the heat pump station, which recovers heat from mine water, are presented in Table 8.

Table 8. Technical and economic indicators of the heat pump station for hot water supply, utilising heat from mine water

1. Technological Indicators of the Heat Pump Station		
Summer Operating Mode (5300 hours)		
Load on the hot water supply system	0,22	MW (hot water +60°C)
Energy transformation coefficient (ETC)	4,40	
Winter Operating Mode (3240 hours)		
Load on the hot water supply system	0,171	MW (hot water +60°C)
Energy transformation coefficient (ETC)	3,04	
2. Annual Electricity Usage by Heat Pumps	296,8	MWh/year
3. Annual Heat Energy Production	779,4	Gcal
4. Existing Prices and Tariffs		
Electricity tariff	102,27	EUR/MWh
5. Investment Costs	150.000	EUR
6. Total Annual Operating Costs	10.000	EUR/year
7. Payback Period	3,5	years

The calculations include a comparison of the cost of producing one gigacalorie (Gcal) of heat using a heat pump station and the cost of heat generated by the mine's boiler plant. For the electricity tariff, the average price of €102,27 per megawatt-hour (MWh) in Austria for 2023 was used. This average was calculated based on the monthly prices, which showed fluctuations throughout the year, with a general decline towards the latter months (ENTSO-E, 2024).

To produce 1 Gcal of heat, 1,163 MWh of electrical energy is required (this is the conversion of Gcal to MWh in the SI system – the globally accepted metric system used as the standard for measurements), and taking the cost of 1 MWh as 102,27 EUR/MWh the cost for producing 1 Gcal using electrical energy is calculated as 102,27 EUR/MWh ·1,163 MWh (or 1 Gcal) = 118,94 EUR at 100% efficiency.

The annual heat energy production using the heat pump station will be:

$$0{,}171 \text{ MW·hour} \times 5.300 \text{ hours} = 906{,}3 \text{ MW or } 779{,}4 \text{ Gcal},$$

Where 0,171 MW·hour is the necessary power consumed by the heat pump to produce hot water, and 5.300 is the number of hours in a year for hot water production using electric boilers.

It is assumed that coal boilers are used during the heating season. By multiplying the numbers, we get the thermal power required for hot water production over the year, and then convert the thermal power from MW to Gcal: 906,3 × 0.86 = 779,4 Gcal.

In the case of using an electric boiler, the electricity costs will be:

779,4 Gcal × 118,94 EUR = 92.701,84 EUR.

For the heat pump system, the annual electricity costs for compressor operation, based on the delivered heat, will amount to 30.353,74 EUR per year. Considering the ETC = 3.04 (the energy transformation coefficient or efficiency of the heat pump), 0,056 MW·hour of electrical energy is required to produce 0,171 MW of thermal energy using the heat pump:

0,171 MW ÷ *3,04 = 0,056* MWh

This results in the following annual calculation:

0,056 MW·year × 5.300 hours × 102,27 EUR/MWh = 30.353,74 EUR/year

779.4 Gcal × 39,17 EUR/Gcal is the cost of producing hot water using the heat pump station. For producing 1 Gcal of thermal energy using the heat pump, 0.383 MWh of electrical energy is required (this accounts for the ETC = 3.04), and 0,383 MWh × 102,27 EUR = 39,17 EUR/Gcal.

As a result, the reduction in annual electricity costs when using heat pumps will be:

92.701,84 EUR – 30.353,74 EUR = 62.348,10 EUR.

The payback period of the project in this case will be:

150.000 EUR ÷ 62.248,10 EUR = 2,4 years.

Thus, using heat pumps can reduce the cost of 1 Gcal of thermal energy by three times compared to the cost of heat generated by an electric boiler. The payback period for the heat pump hot water supply station, which utilises heat from mine water, will be 2,4 years.

Chapter 4 Conclusion

The conducted analysis of corporate sustainability and material flows has demonstrated that obtaining objective information regarding economic, environmental, and social factors is essential for ensuring effective corporate governance and decision-making. For corporate decisions and the management of sustainable development, methods based on the analysis of material and energy flows have proven to be the most effective and appropriate tools for generating coherent information. In most cases, material flows must be considered based on cost and production theory to facilitate corporate decision-making and ensure sustainable development. For these purposes, the material flow cost accounting emerges as a particularly effective tool, serving as a comprehensive cost accounting system.

At the core of MFCA lies a model of material and energy flows that transparently reflects production processes while accounting for key inefficiency factors—namely, waste and defects. MFCA emphasises the processes that transform material and energy flows within quantifiable centers. The theoretical foundations for MFCA's production and cost analysis have been established in work of Dierkes & Siepelmeyer (2019), who developed a differentiated material flow model analogous to other cost accounting systems. This analysis encompasses not only the budgeting process within MFCA based on a complete economic assessment system but also the identification of cost classifications in quantity centers and their grouping by cost categories. Furthermore, a systematic matrix for material flow costs and cost unit accounting is developed.

An important component of MFCA is the comparison of expenses related to products with those associated with material remnants, such as waste, emissions, and wastewater. MFCA enables the acquisition of these data, which can be utilised for the rational application of materials and energy, thereby reducing negative environmental impacts and associated costs. The implementation of MFCA is particularly effective in industries characterised by substantial ecological consequences stemming from material losses in industrial production. Such industries include metallurgy, oil extraction, mining, wood products, furniture manufacturing, and others.

The modelling of material costs in a mining enterprise based on the MFCA concept has demonstrated the feasibility and effectiveness of applying this method in the mining industry. It has also identified avenues for reducing inefficiencies, such as utilising heat from mine water pumped to the surface for heating buildings and miner communities. This process involves extracting low-potential heat from mine water using heat pumps, which is then used to heat water in a secondary pump circuit, resulting in an environmentally friendly method for heating and cooling. Importantly, the operation of these heat pumps does not produce harmful emissions such as CO, CO_2, NOx, SO_2, or PbO_2.

It is shown that the application of the MFCA concept in modelling material flows at the fictitious mining enterprise not only simplifies calculations but also facilitates the integration of additional quantity centers focused on waste processing, thereby enhancing the overall efficiency of the company. For instance, quantity centers could be established for processing waste from enrichment plants, allowing for the extraction of valuable metals and the production of construction materials.

Given the effectiveness of the MFCA method in addressing economic and environmental challenges, it is advisable to consider expanding its application into areas where it is currently not utilised. This includes potential applications in forecasting company development using the Hurst method or addressing social issues within the company. However, these inquiries extend beyond the scope of the present work.

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