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Environmental Cost Accounting of Material Flows During their Technological Transformation

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ABSTRACT

The paper presents selected outputs of the scientific research activities of its authors in the field of implementation, intensification, and standardization of environmental management systems for technological enterprise practice. Aspects of environmental-economic continuity were examined in assessing technological inputs in the form of cost accounting for material and energy flows and the level of environmental quality of transformation processes in the input-output enterprise system. On the basis of these aspects, a model for accounting for the costs and revenues of individual processes was proposed and standardised. The methodological approach to cost accounting consists of ten key elements arranged in Deming's cycle of continuous improvement with a closer specification of their purpose, function, and content. The basis for modelling and quantifying material and energy flows is the determination of input/output points, processes, and the determination of quantification nodes for evaluation in physical and monetary units. For each quantity node, costs for the system and waste management must also be quantified. Energy costs, system costs, and waste management costs are divided into product and material losses from production cost data for each quantity node. Summarisation and integrated presentation of cost data were proposed to utilize cost matrices and Sankey diagrams. Further benefits of using environmental cost accounting for material-energy flows in production were also specified.

Keywords: technological process, material flow, environmental management, cost accounting, quantity node, input/output system, environmental quality of the process.

INTRODUCTION

Management accounting plays a critical role in organizations by applying financial management accounting principles to create, preserve, and enhance enterprise value for stakeholders (Rimmel et al., 2020). It serves as an essential component of management, providing valuable information for business strategy, decision-making, resource allocation, performance improvement, and overall organizational sustainability (Schaltegger et al., 2017)

Emerging trends in management accounting are driven by the need to adapt to dynamic business environments and meet global challenges. These trends focus on various aspects, including improving product quality, reducing corporate costs, increasing productivity, and integrating environmental considerations into production processes (Chovancová et al., 2022, Varaniūtė et al., 2022). Organizations are increasingly recognizing the importance of environmental sustainability and the role of management accounting in addressing environmental issues (Chung et al., 2018, Scarpellini et al., 2020)

In today's business landscape, the integration of environmental and energy management systems has become crucial for effective environmental management accounting (EMA) (Sadowska 2021). Environmental and energy management systems provide organizations with frameworks and tools to manage and account for environmental aspects and impacts (Amann et al., 2022, ISO 2015). They enable a proactive approach to environmental performance and facilitate the optimization of environmental costs (Marrone et al., 2020, Suadiye 2021).

Standardized cost accounting of material and energy flows in organizations represents a powerful tool for aligning economic and environmental objectives, fostering a green economy, and promoting efficiency, environmental performance, and sustainable production (Azapagic et al. 2016, Chovancová et al., 2015). It enables organizations to identify, measure, and manage the environmental costs associated with their operations.

The growing awareness and concern surrounding environmental and energy issues, combined with the increasingly complex global business environment, have compelled companies to address the environmental and energy management challenges. Researchers such as Dhahi et al. (2023), Chen et al. (2022), and Henri et al. (2021) emphasize the strategic importance of accounting for environmental and energy costs within enterprises.

Environmental management accounting (EMA) practices offer businesses a means to promote sustainable growth by facilitating cost reduction, cleaner production methods, competitive advantage (Amann et al., 2022, Jaleel Jafer 2023), improved pricing strategies, and increased shareholder value. As highlighted by Tran et al. (2020), EMA serves as a crucial decision-making tool for managing environmental costs.

However, traditional approaches often overlook the full financial implications of waste, which is a significant, yet hidden burden for businesses, as noted by Rimmel (2020). By solely considering waste disposal costs and neglecting the underlying expenses related to raw materials, labour, and energy, the true cost of waste is not fully captured.

To align economic and environmental objectives, it is imperative to enhance the efficiency in material and energy usage. The adoption of material flow accounting has proven effective in reducing environmental impacts and improving productivity, as exemplified by Taqi et al. (2021), Kokubu-Kitada (2015) and Majernik (2017).

Despite the increasingly acknowledged significance of environmental and energy management in business, there is a literature gap concerning the precise application and effectiveness of material flow accounting as a means to optimize material and energy flows. While research has underscored the advantages of implementing environmental management accounting practices, there is a dearth of comprehensive studies on how material flow accounting can simultaneously advance economic and environmental objectives.

The conducted research tried to fill this void by examining the role of material flow accounting in enhancing material and energy utilisation efficiency within businesses. Specifically, the authors aimed to investigate how the adoption of material flow accounting practices can enhance environmental performance and generate cost savings. Through the examination of real-world instances and a thorough analysis, the authors intended to offer insights into the potential advantages and obstacles associated with incorporating material flow accounting as a strategic tool for sustainable resource management. Ultimately, the study aimed to enrich the existing knowledge base on environmental management accounting and offer practical guidance to businesses striving for economic and environmental sustainability.

METHODOLOGY

The objective of the presented study was to propose a more precise model for the environmental-economic cost accounting of material and energy flows during the technological transformation of corporate inputs (materials, energy, and information) into desired outputs (products). The research must address the questions of economic-environmental continuity and the level of environmental quality in individual processes from the input of materials and energy into the enterprise or technology to the output of both positive and negative products (waste). Such costing of material flows identifies the opportunities for increasing environmental efficiency by highlighting weaknesses in individual processes and the technology as a whole.

Modelling the process ability of cost accounting for material and energy flows

The process of cost accounting for material and energy flows within organisations functions as a forward-looking quantitative management instrument, encompassing a series of structured implementation stages (STN EN ISO 2011). The extent of economic-environmental analysis depends on several factors. These factors include the scale of the organization, the nature of its operations and products, as well as the configuration of its processes. Additionally, it relies on the identification of measurement points and the presence of an environmental management system (EMS). This system may adhere to the ISO 14001 standards or adopt a more informal approach.

Cost accounting of material and energy flows can be conducted within an organization with or without a standard EMS. The process becomes easier, faster, and more efficient when integrated into a certified system based on ISO 14001, and even more streamlined within an integrated management system (IMS) encompassing environmental and energy aspects following ISO 50001 (ISO 2018). Environmental-energy cost accounting of material flows yields valuable information at different stages of the continuous improvement cycle, benefiting both the environmental profile and economic performance of the organization (Nordin et al., 2020).

This approach enables organisations to incorporate financial considerations and forecasts when setting long and short-term development goals. Understanding the potential environmental aspects, impacts, risks, and financial implications of processes enhances the quality of an organisation's environmental profile assessment and provides valuable insights for management decision-making (Allouhi 2022, Kokubu et al., 2023). Figure 1 illustrates the process of implementing the steps involved in environmental cost accounting of material-energy flows within an enterprise, while Table 1 further specifies these steps.

RESULTS AND DISCUSSION

Modelling material and energy flows and costing

In the business environment, and particularly for enterprises, there is a growing need for accurate and visual models that depict the various measurement units (MUs) where materials are stored, used, and transformed. Understanding the transfer of materials between different MUs, such as production and recycling units, is crucial.

In its essence, costing involves distributing system costs, energy expenses, material expenditures, and waste management expenses among the specific material and energy streams within a company. Once all costs associated with a specific MU have been identified (through positive and negative product analysis), they are further assigned and distributed to the outputs of each MU within the production process of a specific product. This allocation is based on the proportion of material inputs and the corresponding material losses.

Inputs and outputs of business processes

The overall balance of material and energy flows within an enterprise is founded on the

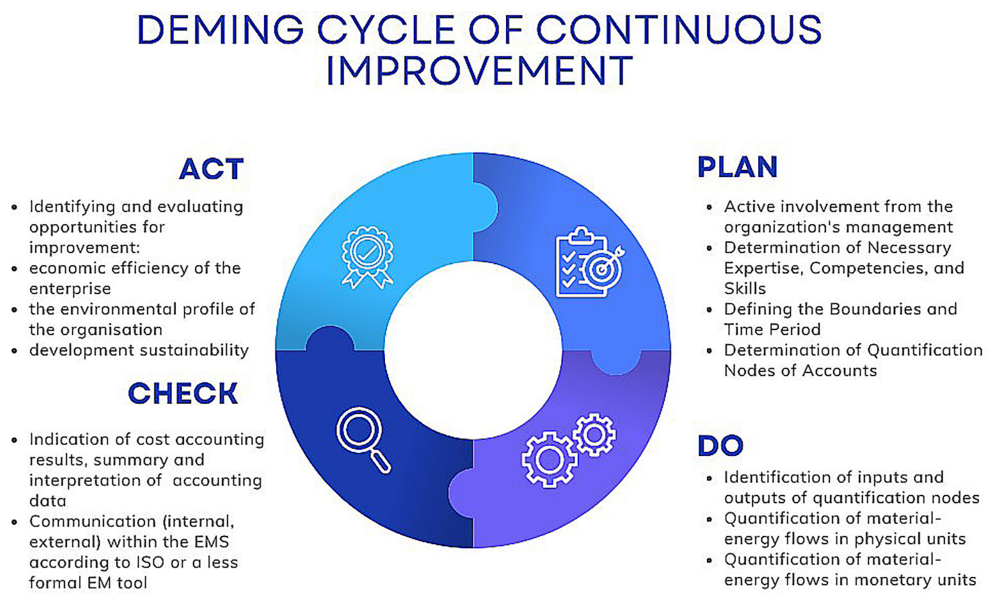

Figure 1. Cost accounting model of an organisation's material and energy flows – standardising the process ability in the P-D-C-A cycle

Table 1. Hierarchy of cost accounting steps for material and energy flows

Step	Description
1 Management involvement	The effective implementation of accounting practices requires strong support from top management within the organization. Management should actively participate in the process by providing leadership during implementation, assigning roles and responsibilities, allocating necessary resources, monitoring progress, reviewing results, and making decisions to improve the environmental-economic profile.
2 Determining the required expertise	A comprehensive range of expertise is needed, particularly in areas such as operations design, production procurement, and technical knowledge related to material and energy flows within the organization. This includes understanding the implications of processes, quality management, corrective actions for environmental management, and knowledge of environmental aspects, impacts, and risks (EAI&R). Additionally, expertise in cost-benefit accounting for material and energy flows is essential.
3 Defining boundaries and time period for accounting analyses	Organizations have the flexibility to determine the boundaries for accounting analyses, whether it involves a single process, multiple processes, an entire facility, or a supply chain. It is crucial to focus on processes with significant EAI&R potential. The time period for data collection should be sufficiently long to capture all relevant data and variations in processes, such as monthly, multiple months, six months, or a year. The time period can be aligned with the production of specific product items, for example.
4 Identifying quantification nodes (qns)	Various processes can be designated as quantification nodes (QNs) within the accounting framework. Examples of QNs include material receiving, semi-finished goods splitting, storage, intermediate storage, machining, welding, shipping, and others. The selection of QNs is based on process information. Additional measurement units (MUs) can be determined at locations with significant material losses, such as energy for transportation, oil leaks, pressurized air, or system costs.
5 Identifying inputs and outputs for each mu	For each measurement unit (MU) within the accounting boundaries, it is essential to identify inputs (materials and energy) and outputs (products, material losses, and energy losses). Energy and energy losses can either be included in the materials and material losses or estimated separately, depending on the organization's discretion. Identifying inputs and outputs for MUs facilitates the linking of MUs within the cost accounting boundaries, enabling interrelated evaluation of MU data throughout the system under study.
6 Quantifying material flows in physical units	For each MU, it is necessary to quantify inputs and outputs in physical units, such as weight, number of pieces, volume, length, etc. These measurements should be converted into a standardized unit (e.g., weight) to enable material balances for each MU. Material balance requires ensuring that the total quantity of outputs (products and material losses) equals the total quantity of inputs. All materials within the accounting boundaries should be quantified, while materials with minimal environmental or financial significance may be excluded.
7 Quantification of material flows in monetary units	MATERIAL COSTS For each measurement unit (MU), it is necessary to quantify the costs of inputs and outputs, including products and material losses. These costs can be determined based on various factors such as historical data, current costs, or costs for reproduction, depending on the organization's chosen cost accounting method. Additionally, material costs associated with changes in material inventory within each MU should also be quantified. ENERGY COSTS Energy costs need to be quantified for each MU in terms of energy consumption. If the energy costs of individual tasks are unknown or challenging to measure, the total energy costs of the selected processes should be allocated among the MUs. Subsequently, the energy costs within each MU should be divided between products and material losses. SYSTEM COSTS System costs encompass all in-house material handling costs, excluding material, energy, and waste management costs. These costs include labour, depreciation, maintenance, transportation, and other relevant expenses. If the costs within each MU are unknown or difficult to measure, they should be allocated to the total system costs of the selected processes among the MUs. Afterwards, the system costs of each MU should be apportioned between products and material losses. WASTE TREATMENT COSTS Waste treatment costs pertain to the expenses associated with managing material losses generated within each MU. It is essential to quantify these costs for each MU.
8 Summarization and interpretation of accounting data	The data acquired during the accounting analysis should be summarized in a format suitable for further interpretation, such as a material flow cost matrix or a material flow diagram. Summarized data allows organizations to identify MUs with significant environmental and financial material losses. These MUs can then undergo more detailed analysis and can be aggregated for the entire process under examination.
9 Communication of accounting results	The outcomes of the accounting analysis should be effectively communicated to relevant stakeholders both within and outside the organization. This includes internal communication with management and external communication with stakeholders. The information derived from the accounting analysis can support decision-making processes aimed at improving both environmental and financial performance. Additionally, it can assist in developing effective communication tools to engage stakeholders.
10 Identifying and assessing opportunities for improvement	Identifying opportunities for improvement is a crucial aspect of cost accounting for material and energy flows in an organization. Actions aimed at achieving improvements may involve material substitution, modifications to production line processes or products, and the identification of research and innovation activities focused on enhancing material and energy efficiency. The cost accounting process not only facilitates improvements in accounting and information systems but also opens up avenues for overall organizational improvement.

recognition that whatever enters the enterprise must also exit the enterprise at some point. This includes all input materials, energy, information, as well as products and by-products. It is crucial to compare the procured inputs with the total production volume, sales statistics, and waste and emissions records. The objective is to enhance the company's efficiency in utilising materials and energy, leading to improvements in economic, environmental, and energy aspects.

The cost accounting process is depicted in Figure 2. For instance, out of 100 kg of raw material input, 30 kg is allocated to material losses. Consequently, the total costs are distributed in this ratio, except for waste management costs, which are only allocated to material losses. This is because only the material losses require additional processes and financial resources for waste management.

The values in Figure 2 are fictional and can be used as a case study. It illustrates the modelling principle. Of course, if another company uses this model, in specific research, it will substitute the values that are realistically applicable to that particular company.

The modelling and models serve as representations of the overall material flows within the chosen boundaries for cost analysis. The specification of material costs can generally be categorised into two situations:

- Simple production process – this involves tracing the flow of each material and energy from start to finish, from input to output. In this case, it is possible to track and identify the contribution of each material and energy input in the final products. The simple production process refers to a manufacturing or operational method that involves relatively few steps, components, or stages. In this process, the sequence of operations is straightforward, with minimal variations or complexities. It typically requires basic equipment, straightforward procedures, and involves a low level of coordination among workers or machinery. Simple production processes are often characterised by their efficiency, ease of management, and low risk of errors.
- Complex process – in more complex processes, the initial material and energy inputs are transformed into intermediate inputs, which cannot be individually recognised in the final products. In such cases, the intermediate products are considered as outputs. Please refer to Figure 3 for a visual representation.
- Complex process – the complex process is a manufacturing or operational method that involves numerous interconnected steps, components, or stages, resulting in a high degree of intricacy and sophistication. Complex processes typically require advanced technology,

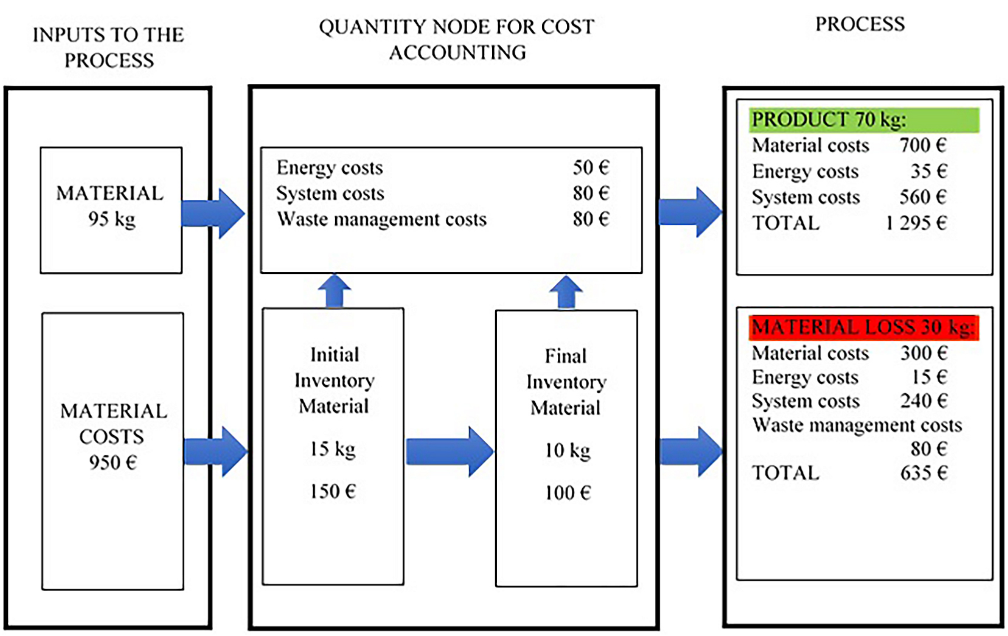

Figure 2. Calculation of process costs in accounting for material and energy flows in an enterprise

Note: Green colour – desired product, Red colour – undesired product.

specialised equipment, and highly skilled personnel to execute successfully. These processes often involve intricate coordination among multiple departments, machines, or individuals, and may entail various interdependencies and potential points of failure. Complex processes often require careful planning, monitoring, and optimisation to ensure efficiency and effectiveness.

In a simple production process, two measurement units (MUs) are defined, each generating a product and a corresponding material loss. However, for more intricate processes, the consideration of intermediate products as outputs becomes necessary to accurately capture the material flows. Material-energy flow model including semi-finished products is presented in Figure 3. This model corresponds to a simple production process.

The precise composition of semi-finished product flows and material losses is often unknown in complex systems, making it challenging to calculate the exact unit material cost for these material-energy flows. Table 2 presents the material costs associated with the model depicted in Figure 3. Please note that for the sake of simplicity, the table does not encompass all costs within the measurement unit (MU). The total unit material cost has been estimated by considering the cost of the initial material inputs at 77.5 €/kg.

Ideally, energy, system, and waste management costs, along with their distribution to products and material losses, are derived directly from existing production cost records for each measurement unit (MU). Alternatively, if direct derivation is not feasible, these expenses can be approximated using other accessible data sources, such as standardised energy management metrics employed by the organisation.

There are four methods that can be employed:

1) Allocating energy, system, and waste management costs between MUs: The costs of measurement units (MUs) can be quantified using more aggregated data for the entire process or technical installation in two sequential steps. Initially, these costs are computed for the entire process within the boundaries of cost accounting. Subsequently, they are allocated to individual MUs based on an appropriate criterion, such as machine time, production volume, number of employees, hours worked, production area, etc. Table 3 provides an example of such a breakdown for a specified period.
2) Allocating energy, system, and waste management costs to products and material losses in each MU: In this approach, all waste management costs are attributed to material losses. Table 4 illustrates such an allocation for a specific period using the percentage distribution of material in MU1 and MU2 as the criterion. For example, in MU1, 87.5% of the material is allocated to products (70/80 kg), while 12.5% is allocated to material losses (10/80 kg). Similarly, in MU2, 66.67% is allocated to products (60/90 kg), and 33.33% is allocated to material

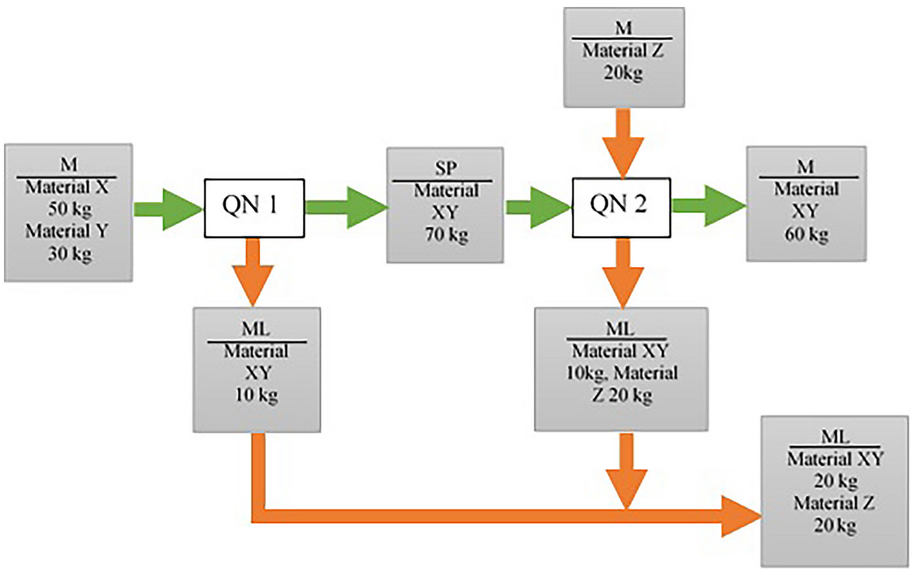

Figure 3. Material-energy flow model including semi-finished products

Note: M – material or energy, ML – material-energy loss, QN – quantity node, SP – semi-finished product. Green arrow - finished product flow, orange arrow - material loss flow

Table 2. Material costs in the intermediate process (EUR)

Composition of products and material losses	Production result (weight-kg)	Unit cost (€/kg)	Total (€)
Products	60		4650
Material XY	60	77.5	4650
Material Z	0	20	0
Material losses	40		1950
Material XY	20	77.5	1550
Material Z	20	20	400
Total	100		6600

Table 3. Breakdown of energy, system and waste management costs (EUR)

Cost types	MU1	MU2	Total
Energy costs	400	300	700
System costs	800	1200	2000
Waste management costs	300	400	700

Table 4. Distribution of energy, system and waste management costs per products and material losses in MU1 and MU2 (EUR)

Cost types	MU1	MU2
Energy costs	400	300
Products	350	200
Material losses	50	100
System costs	800	1200
Products	700	800
Material losses	100	400
Waste management costs	300	400
Products	0	0
Material losses	300	400

losses (30/90 kg) (Majernik 2017). The values in Table 2 (similarly, the values in Tables 3 and 4) summarise and interpret the data that are input in Figure 2.

3) Alternative to percentage distribution of material: Instead of using a percentage distribution of material based on weight, an alternative approach can be employed. This alternative approach utilises the weight distribution of all materials in each MU as the allocation criterion. If this is not feasible, the percentage distribution of the main material directly related to the process is used as the criterion.
4) An alternative approach to the allocation criteria for energy consumption: The common criterion for allocating energy consumption between products and material losses is the mass distribution of material inputs. However, if more detailed information on the energy efficiency of machines in the MUs is available, a more accurate quantification of inefficiency and energy waste can be implemented (Figure 4). For example:
   a) if 10% of a machine's operation represents idle running, this portion of energy is allocated to material losses rather than products;
   b) a material inefficiency of 20% results in allocating 80% of the remaining energy consumption to products;
   c) a 15% reduction inefficiency from the optimal state leads to allocating only 85% of the increased energy consumption to products.

When employing the alternative approach, the energy consumption in MUs is divided as follows:

- energy allocated to products: 90%, 80%, 85%, 61.2%;
- energy allocated to material losses: 100% – 61.2% = 38.8%.

The higher percentage of energy allocated to material losses in the alternative approach indicates inefficiency and highlights the opportunities for improvement.

Integrated presentation and analysis of cost data

Material, energy, system, and waste management cost data can be summarised in various ways to facilitate further analysis and utilisation. In the considered case study, a material flow cost

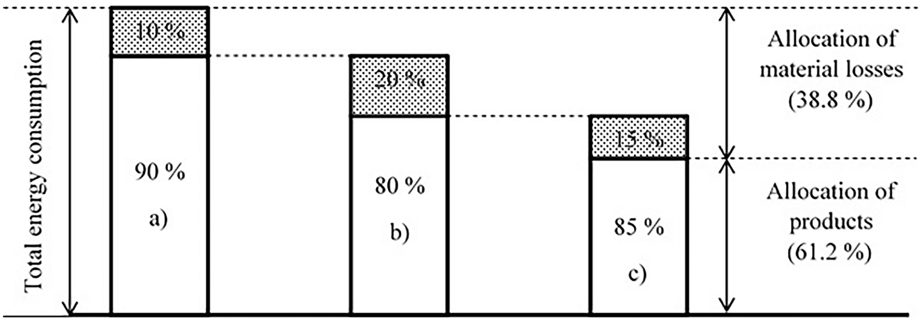

Figure 4. Quantification of energy losses

matrix was presented in Table 5, it incorporates the data for the two measurement units (MUs) examined in Figure 3. Additionally, Figure 5 visually represents this information through a clear and informative Sankey diagram.

The energy costs in MU2 were determined to be €433 for products and €217 for material losses, based on the percentage material distribution in MU2 (66.67% for products and 33.33% for material losses). The total energy cost amounts to €650, which comprises the energy cost of products in MU1 (€350) and the new input in MU2 (€300).

Similarly, the system cost in MU2 was calculated as €1,270 for products and €633 for material losses, using the percentage material distribution in MU2 (66.67% for products and 33.33% for material losses). The overall system cost totals €1,900, consisting of the system cost for products in MU1 (€700) and the new input in MU2 (€1,200).

Implications and benefits of adopting material-energy flows accounting

By combining the principles of environmental management systems and rigorous accounting methodologies, companies can achieve significant improvements in both economic efficiency and environmental performance, including:

- Cost reduction: the implementation of a functional environmental management system and the adoption of cost accounting practices for material-energy flows can yield significant cost reductions for companies. By meticulously tracking and analysing material and energy costs, organisations can identify the areas of inefficiency and waste, leading to the implementation of cost-saving measures, resource optimisation, as well as reduction of material and energy losses. This proactive approach enables companies to achieve improved profitability by minimising production costs.
- Environmental performance: the establishment of an environmental management system and the integration of cost accounting practices focused on material-energy flows empower companies to assess and address their environmental impacts. Through quantification and analysis of these impacts, organisations can develop effective strategies to mitigate their carbon footprint, minimise waste generation, and enhance overall environmental performance. This comprehensive approach ensures that companies prioritise sustainability

Table 5. Material-energy flow cost matrix (EUR): period 20xx

Specification	MU1 – costs in EUR					MU2 – costs in EUR				
	Material	Energy	System	Waste management	Total	Material	Energy	System	Waste management	Total
Inputs from previous MU						5200[a]	350[b]	700[c]		6250
New entries to MU	6200	400	800	300	7700	400	300	1200	400	2300
Total in each MU	6200	400	800	30	7700	5600	630	1900	400	8550
Products	5200	300	700		6250	4200	433	1267		5900
Material losses	1000	50	100	300	1450	1400	217	633	400	2650
Total material losses in the process						2400	267	733	700	4100
Total costs in the process						6600	700	2000	700	10000

Note: a , b , c , d – values of costs transferred from MU1 to MU2; the data have been taken from Tables 2, 3, 4.

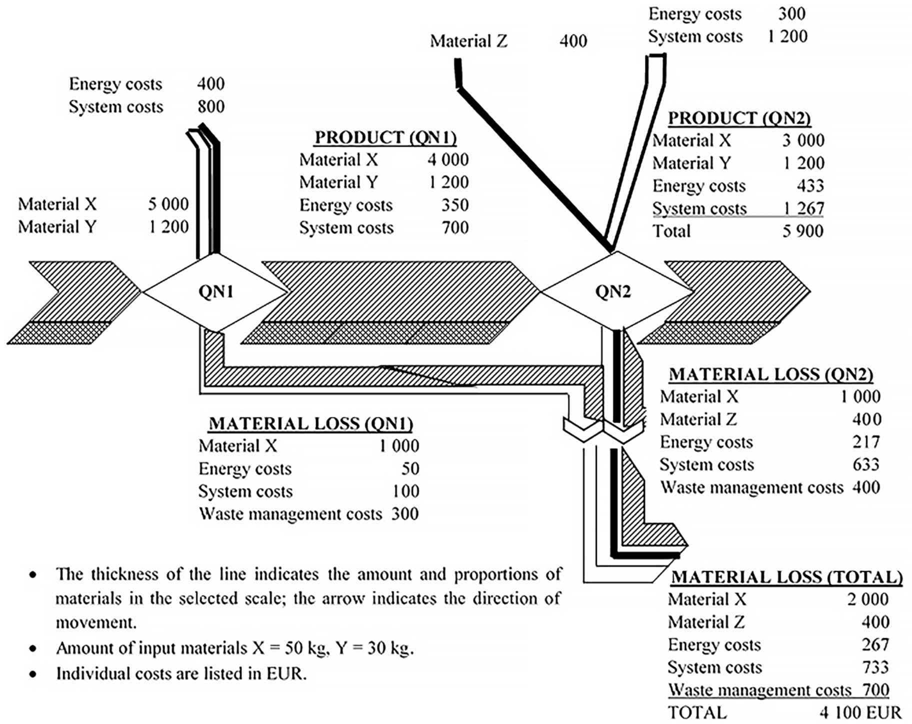

Figure 5. Informative Sankey diagram

objectives and contribute to the preservation of the environment.

- Regulatory compliance: stringent environmental regulations and requirements are imposed by regulatory bodies on businesses across various industries. By implementing an environmental management system aligned with ISO standards and employing accurate cost accounting practices for material-energy flows, companies can ensure compliance with these regulations. The ability to precisely track and report environmental performance facilitates audits and regulatory inspections, enabling companies to demonstrate their adherence to regulatory guidelines effectively.
- Sustainable supply chain: extending the material-energy flow cost accounting system to encompass the supply chain enables collaborative efforts between companies, suppliers, and customers to optimize resource utilisation and improve environmental performance. This integrated approach fosters sustainable practices throughout the entire value chain, promoting the achievement of sustainability objectives and enhancing the reputation of all stakeholders involved.
- Decision-making and goal setting: the availability of reliable and accurate data on material-energy flows empowers informed decision-making and goal setting within organisations. By leveraging this data, companies can identify the areas for improvement, establish realistic targets for reducing material and energy consumption, as well as effectively track progress towards sustainability goals. This data-driven approach facilitates strategic decision-making that aligns economic and environmental objectives, enabling companies to make informed choices that balance financial viability with environmental responsibility.

The contribution represents a fragment of original research conducted as part of the preparation of a Slovak Technical Standard (STN) for EN ISO 14051 (prepared by Majerník and colleagues).

The novelty of the proposed solution lies in changing the approach to evaluating continuous improvement within the environmental process management of the enterprise and its technology. Environmental cost accounting according to the proposed model transforms existing approaches to corporate accounting (only at input and output) into the quantification of costs at multiple key quantity nodes. Such an approach allows for identifying weaknesses in transformational technology and its individual processes, which are potential areas for increasing environmental-economic efficiency and developmental sustainability of production.

CONCLUSIONS

The global consumption of materials and energy has been steadily increasing in recent years, despite the implementation of various regulatory measures at both global and regional levels. In the manufacturing industry, for instance, material and energy costs account for approximately 50% of a company's total expenses. Reducing their consumption can lead to tangible economic and environmental benefits, such as savings in material, energy, and waste management expenses.

The key solution to address the challenges faced by companies lies in implementing a functional environmental management system that is built and certified according to the international standards of the ISO 1400 family. The conducted research in this field highlights that cost accounting of material-energy flows, as a management tool, enables a comprehensive improvement of both the economic efficiency and environmental performance of the product system. This approach allows for the examination and enhancement of the transformation process from inputs to desired outputs.

By employing more precise cost accounting models for material-energy flows, the data becomes readily demonstrable, accessible, and useful in the continuous pursuit of optimisation opportunities. It also aids in setting realistic economic and environmental development goals for the enterprise. A material-energy flow cost accounting system, adhering to ISO standards, can be implemented in various types of enterprises, economies, and industries, with the potential for extension to the entire supply-customer chain.

Through research and the development of a more precise model for cost accounting of material flows in transformational technology, knowledge in the field of standardisation and intensification of environmental management systems has been expanded. The procedure can also be used as a superstructure for a standard EMS system established in the enterprise according to STN EN ISO 14001 and registered in the European EMAS III scheme. From this perspective, the model replaces the currently used subjective assessment of environmental aspects, impacts, and risks from the register with an objective quantification of the environmental quality of individual material conversion processes and energy consumption.

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REFERENCES

1. Allouhi, A. 2022. Techno-economic and environmental accounting analyses of an innovative power-to-heat concept based on solar PV systems and a geothermal heat pump. Renewable Energy, 191, 649–661.
2. Amann, B., Jaussaud, J., Mizoguchi, S., Nakamura, H. 2022. Environmental management accounting in European countries and Japan: A literature survey. Sustainable development in Asia: socio-economic, financial and economic perspectives, 167–177.
3. Azapagic, A., Stamford, L., Youds, L., Barteczko-Hibbert, C. 2016. Towards sustainable production and consumption: A novel decision-support framework integrating economic, environmental and social sustainability (DESIRES). Computers & Chemical Engineering, 91, 93–103.
4. Chen, M., Liu, Q., Huang, S., Dang, C. 2022. Environmental cost control system of manufacturing enterprises using artificial intelligence based on value chain of circular economy. Enterprise Information Systems, 16(8–9), 1856422.
5. Chovancová, J., Huttmanová, E. 2015. Possibilities of management systems implementation with focus on their mutual integration. Hradec Economic Days (13th International Scientific Conference on Hradec Economic Days). 5(1), 292–298.
6. Chovancová, J., Rovňák, M., Shpintal, M., Shevchenko, T., Chovanec, F. 2022. Perception of benefits and barriers associated with the management systems integration-a comparative study of Slovak and Ukrainian organizations. TEM Journal, 11(2), 772.
7. Chung, J., Cho, C. H. 2018. Current trends within social and environmental accounting research: a literature review. Accounting Perspectives, 17(2), 207–239.
8. Dhahi, H. N., Abdullah, H. S. 2023. The use of material flow cost accounting in supporting the cost of a sustainable product to achieving green productivity. International Journal of Research in Social Sciences and Humanities, 13(1), 189–204.
9. Henri, J. F., Journeault, M., Rodrigue, M. 2021. The domino effect of perceived stakeholder pressures on eco-controls. Accounting and the Public Interest, 21(1), 105–136.

10. ISO 2018. ISO 50001:2018 - Energy management systems - requirements with guidance for use.
11. Jaleel Jafer Al Mosaoy, D. 2023. The role of environmental management accounting information in the design process of environmental and sustainable products. International Journal of Engineering Business Management, 15, 18479790231183511.
12. Kokubu, K., Kitada, H. 2015. Material flow cost accounting and existing management perspectives. Journal of Cleaner Production, 108, 1279–1288.
13. Kokubu, K., Kitada, H., Nishitani, K., Shinohara, A. 2023. How material flow cost accounting contributes to the SDGs through improving management decision-making. Journal of Material Cycles and Waste Management, 1–11.
14. Majerník, M. 2017. Environmental business economics, edition of scientific and professional literature EUBA. Typopress s. r. o., Košice, 250
15. Marrone, M., Linnenluecke, M. K., Richardson, G., Smith, T. 2020. Trends in environmental accounting research within and outside of the accounting discipline. Accounting, Auditing Accountability Journal, 33(8), 2167–2193.
16. Nordin, N. K. Z. B., Hamid, M. A., Sapingi, R. 2020. Environmental management accounting practices and environmental performance in Malaysian manufacturing industry. Global Business and Management Research, 12(4), 160–166.
17. Rimmel, G. 2020. Accounting for sustainability. 1st edition, Routledge, New York, 230.
18. Sadowska, B. 2021. The costs and cost accounting model (simplified) in State Forests National Forest Holding. Zeszyty Teoretyczne Rachunkowości, 113, 233–253.
19. Scarpellini, S., Marín-Vinuesa, L. M., Aranda-Usón, A., Portillo-Tarragona, P. 2020. Dynamic capabilities and environmental accounting for the circular economy in businesses. Sustainability Accounting, Management and Policy Journal, 11(7), 1129–1158.
20. Schaltegger, S., Burritt, R. 2017. Contemporary environmental accounting: issues, concepts and practice. Routledge.
21. STN EN ISO 2011. STN EN 14051: 2011. Environmental management. Material flow cost accounting. General framework.
22. STN EN ISO 2015. STN EN ISO 14001:2015 - Environmental management systems - Requirements with guidance for use.
23. Suadiye, G. 2021. Contemporary Developments on Sustainability Accounting and Reporting: An Overview Perspective. Auditing Ecosystem and Strategic Accounting in the Digital Era: Global Approaches and New Opportunities, 59–86.
24. Taqi, M., Rusydiana, A. S., Kustiningsih, N., Firmansyah, I. 2021. Environmental accounting: A scientometric using biblioshiny. International Journal of Energy Economics and Policy, 11(3), 369–380.
25. Tran, N. H., Hoang, T. H., Nguyen, T. T. H. 2020. Environmental management accounting perception and implementation in the automobile industry in Vietnam. The Journal of Asian Finance, Economics and Business, 7(12), 941–949.
26. Varaniūtė, V., Žičkutė, I., Žandaravičiūtė, A. 2022. The changing role of management accounting in product development: directions to digitalization, sustainability, and circularity. Sustainability, 14(8), 4740.