Rebirth of Material Flow Cost Accounting (MFCA) to Achieve Efficiency Increases, Greenhouse Gas Reductions, and Economic Improvements

An Innovative Approach for Manufacturing Companies Based on MFCA 2.0

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Lastly, I turn towards the Creator of all things, who has been my guiding light throughout this journey. I am very grateful to Jesus and he deserves my highest praise.

The Son is the image of the invisible God, the firstborn over all creation.
For in him all things were created: things in heaven and on earth, visible and invisible,
whether thrones or powers or rulers or authorities;
all things have been created
through him and for him.
Colossians 1:15–16

Pforzheim, June 12, 2025 Aline Bauer

Abstract

Material flow cost accounting (MFCA) is a valuable and effective method of environmental management. Also rooted in the discipline of accounting, MFCA combines monetary and environmental indicators to assess material losses in production processes. Although the method is capable of empowering manufacturing companies and was first standardized with the ISO 14051 in 2011, it has not yet become widespread in practice. Several weaknesses, including an incomplete application cycle, led to the rebirth of MFCA as *MFCA 2.0*, as outlined in this dissertation. The objective of this work was to enhance the method's practical orientation, thereby enhancing its relevance to the manufacturing industry. The development of MFCA 2.0 was inspired by and built upon the development history of cost accounting. Particular emphasis was placed on the methodological debate led by the two German professors Wolfgang Kilger and Paul Riebel. They both sought to develop a novel cost accounting approach. Throughout their active careers and research activities, they produced a considerable number of publications, which were viewed and utilized for this research. This dissertation theorized Riebel's identity principle as fundamental concept and employed it for the methodological advancement. The implementation of a tangible improvement measure can be understood as the starting point for calculating the scenario-based saving potential of a given system based on the improvement measure. Consequently, MFCA 2.0 surpasses the standard ISO 14051, and the method is complemented by a consulting concept that employs a consecutive approach. This methodological improvement was developed to increase resource efficiency, rather than merely detecting existing inefficiencies. Hence, the method does not only enable transparency, but now also enables effective cost and emission control through resource-efficient manufacturing processes. MFCA 2.0 is a vital tool for companies striving to be future-oriented, sustainable, and globally competitive. Building on hardly recognized ideas from the history of cost accounting, this work presents an argument and a tangible means for a more resource-efficient and cleaner production—addressing both research and practice: On the one hand, MFCA 2.0 and the consulting concept provide a theory-based methodological contribution to research, and, on the other hand, they offer a practice-oriented method to industries that strive for environmental and economic improvements.

Keywords: material flow cost accounting, cost accounting for sustainability, environmental management accounting, resource efficiency, cleaner production

Context of This Dissertation

The research presented in this dissertation was conducted during and after the research project MaFImA— Material Flow-based Improvement Assessments. The MaFImA project team—of which I was a member—aimed at advancing sustainable production practices through innovative cost accounting methods and the software tool *Umberto 11*®. Within this project framework, my doctoral studies contributed to the development and improvement of material flow cost accounting (MFCA), addressing both theoretical foundations and practical implementation challenges.

The MaFImA project provided a valuable interdisciplinary platform, fostering collaboration between academic researchers, industry partners, and sustainability experts. This environment enabled a comprehensive analysis of the method's potential and laid the groundwork for my dissertation. The scenario-based algorithm of MFCA 2.0 was invented and implemented in software by Andreas Möller. The project team focused on the practical application of the algorithm and the software tool, leading to the advancement of the algorithm and the software. This dissertation placed the algorithm in the context of cost accounting theory and complemented the new approach with an MFCA 2.0 consulting concept. The final report of the MaFImA research project can be downloaded using the following link: https://pd.lubw.de/10652

Additionally, I presented this research to a broader audience of two international research conferences. Some initial research ideas and results were presented to the audience of the Third NIBES Research Conference, which took place online on November 23, 2021. NIBES is a Network of International Business and Economics Schools, consisting of 21 business and economics schools in 21 countries, and it organizes an annual conference.

Moreover, part of this research was presented at The International Conference on EcoBalance in Fukuoka, Japan, on November 2, 2022. During this trip to Japan, I had the opportunity to meet Professor Michiyasu Nakajima in Nara. I could experience Michi's extraordinary hospitality and I deeply appreciated our conversations about environmental management in general and the MFCA method in particular. Unfortunately, Michi passed away just before the submission of this work in 2025. He will be fondly remembered.

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Abbreviations

ABC	activity-based costing
AGPLAN	Arbeitsgemeinschaft Plankosten (in English: Working Group for Standard Costs)
APA	American Psychological Association
B	billion
BAU	business as usual
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (in English: Federal Institute for Geosciences and Natural Resources)
BMU	Bundesumweltministerium (in English: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
CIP	continuous improvement process
COVID-19	Coronavirus disease 2019
CO_2e	carbon dioxide equivalents
CSD	Commission on Sustainable Development
CSDDD	Corporate Sustainability Due Diligence Directive
DOE	Design of Experiments
EBIT	earnings before interest and taxes
EDV	electronic data processing
EPD	Environmental product declaration
ERP	Enterprise resource planning
EU	European Union
EUR	Euro
GHG	greenhouse gas
IRP	International Resource Panel
ISO	International Organization for Standardization
kWh	kilowatt-hour
KVP	kontinuierlicher Verbesserungsprozess (in English: continuous improvement process, CIP)
LCA	Life cycle assessment
M	million
MFCA	material flow cost accounting
mgmt	management *[in tables only]*
N.A.C.A.	National Association of Cost Accountants
NAA	National Association of Accountants

OECD	Organisation for Economic Co-operation and Development
OEE	overall equipment effectiveness
PDCA	plan-do-check-act
QC	quantity center
R&D	Research and development
ROI	return on investment
SDG	Sustainable Development Goal
SME	small and medium-sized enterprise
UBA	Umweltbundesamt (in English: Federal Environment Agency of Germany)
UN	United Nations
UNCED	United Nations Conference on Environment and Development
VDI	Verein Deutscher Ingenieure (in English: The Association of German Engineers)
WCED	World Commission on Environment and Development
WWI	First World War
WWII	Second World War

Symbols

a–i	material flows as defined in Figure 20
ef	efficiency factor of a production process
if	improvement factor
m	mass of the material input flow in a QC
p	number of product units produced in a given time period, e.g., per month
sp	saving potential
x	reduction of material loss flow *g*
y	reduction of material loss flow *h*
z	reduction of material loss flow *i*

1 A Brief Journey Through the Concept of Sustainability

Be the change that you wish to see in this world.—Mahatma Gandhi

Doctoral studies are an exciting adventure with a clear vision and high expectations regarding their results. That is because the results are not an end in themselves, but every doctoral student seeks truth in their work and aims to make a significant contribution to academia and human progress. These contributions may be as manifold as the world of academia with all its different facets, but they share the same wish: to translate this wish into a tangible positive change. The present dissertation has been devoted to the field of sustainability studies, and its aim is to contribute to sustainable development of this planet and its population.

1.1 Introduction to Sustainability: Back to the Roots

Sustainability is undoubtedly a buzzword of the 21st century and one of the main challenges of this time. Although it has been subject of debate in research and practice for several centuries—to give away the end of this section—there is no clear-cut definition of the term. Perhaps that is what makes the public debate so lively and continually fuels it. Taking a closer look at the word, it is a noun that consists of two parts: *sustain* and *ability*. Applied to humankind living on planet Earth, these two words suggest the meaning of the *ability to sustain itself*. This rather basic starting point opens the stage for many further questions and discussions to understand and apply the term.

In this discourse, a spiritual approach to the term shall be included by briefly sketching two ideas. First, the Torah and hence also the Bible contains an instruction for humankind to preserve the environment: "The Lord God took the man and put him in the Garden of Eden to work it and take care of it." (*New International Version*, 2011, Genesis 2:15) This sentence draws a clear picture of the relationship between nature and humankind. Second, Pachamama is a goddess that exists in Inca mythology, and who is worshipped until today by South American indigenous peoples in the Andes Mountains. The name *Pachamama* can be translated as "Mother Earth" and Pachamama is characterized as a type of goddess who decides over fertility, farming, the mountains and earthquakes (Zaffaroni, 2011). It is an approach to sustainability that aims to reconnect nature and humankind by granting Pachamama rights that need protection. Over time, this approach has played a role in environmental struggles and gained political meaning, for example, in Ecuador, Bolivia, and also among some public authorities in the United States (Humphreys, 2017; Kaijser, 2014; Tola, 2018). These spiritual approaches can be seen as arguments in favor of environmental protection. The Torah describes the environment as our habitat, whereas Pachamama is described as a living creature with rights that should be asserted.

Consequently, the indefinite extraction of natural resources from the environment can be understood as transgression. Bardi's (2014) book title *Extracted: How the Quest for Mineral Wealth Is Plundering the Planet* fortifies this emotive view. Either way, humankind is called to use natural resources in an economical and efficient manner. The specific idea of sustainability in a narrower sense was recognized and put into words at the beginning of the 18th century already, as will be shown shortly hereafter.

German language translates sustainability with the term *Nachhaltigkeit*, which has the literal meaning of *holding after* in the form of a noun. This explicitly introduces a time dimension to the concept of sustainability. Therefore, the term is often used in combination with development over time, resulting in *sustainable development*. The idea behind this term is that sustainability cannot be reached per se, but rather be aimed for in the form of *sustainable development*. Thus, this idea sets the direction for change, pointing the way towards a more sustainable future. The United Nations' Report of the World Commission on Environment and Development (WCED), *Our common future*, also known as *The Brundtland Report* named after the Commission's chairwoman Gro Harlem Brundtland, contains the following definition of the term *sustainable development*:

> Humanity has the ability to make development sustainable – [sic] to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits – [sic] not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities. (WCED, 1987, chapter I, para. 27)

This statement emphasizes the temporal aspect by pointing to future generations and their needs. Moreover, it explains that the limits of sustainable development depend on technology, among other factors. Technology, in turn, is not a constant factor, because it can be influenced by human activities.

Taking a closer look at the origin of the term, the idea was already expressed and published in 1713 by Hans Carl von Carlowitz, whose work was reissued by Hamberger in 2022 in its original text with additional materials. Von Carlowitz was a German cameralistic accountant who published the first cohesive work on the topic of forestry. The work is titled *Sylvicultura Oeconomica, oder Haußwirthliche Nachricht und Naturmäßige Anweisung zur Wilden Baum-Zucht*, which literally translated means "Economic forestry, or domestic message and natural instructions for wild tree cultivation" [own translation]. Von Carlowitz' motivation for this work was the rising wood shortage as forests were being excessively cleared. He recognized this danger and addressed it with his work on the topic of forestry. It depicts the idea and goal of how wood can be cultivated and regrown in a way that it can be used continuously in the long run because it is an indispensable component for a country's future existence (von Carlowitz, 1713/2022). To achieve this goal, only a certain number of trees can be cut in a particular time period. The number equals the amount that can regrow in that specific time period. Von Carlowitz also included the intergenerational aspect in his work and suggested that the raw material peat should be used as substitute for the energy carrier wood in order to make provisions for the next generations. He considered this an economical and precautionary piece of advice and interestingly, he comments that humans act only when it is almost too late.

An important aspect is that wood is a renewable natural resource and von Carlowitz realized that wood was an important, scarce resource. Therefore, he suggested sowing and planting trees as measure against the imminent wood shortage. Furthermore, he argued that compared to metal supply, wood was the critical factor because it was necessary at that time to extract and process metal ore. Compared to wood, metal ore deposits are not considered renewable within a foreseeable timescale. Although von Carlowitz did admit that the amount of metal ores was not quantifiable, he considered natural metal deposits to be inexhaustible (von Carlowitz, 1713/2022). He saw his theory confirmed by other scholars who worried about forthcoming wood and coal shortages. Nowadays, more than 300 years after von Carlowitz' work, we still do not know the total amount of minerals in the Earth nor their availability. However, there is research showing that the availability of resources significantly depends on the energy input factor. More precisely, the energy demand for the mining and the extraction of metals increases with the falling ore grade (Rötzer, 2023).

Moreover, the *Sylvicultura Oeconomica* contains multiple ideas that are relevant and useful for the present work. Von Carlowitz‘ work is based on the idea that the availability of natural resources is limited, and he discussed the imminent problem of a wood shortage in order to develop practical solutions. Besides the imperative to sow and plant trees, von Carlowitz formulated several ideas. Chapter 4 of the *Sylvicultura Oeconomica* analyzes the production process and different uses of wood. This includes uses of wood in households like cooking, baking and heating, and the chapter mentions major consumers, such as the construction, brewing, mining, and metal industries. Von Carlowitz (1713/2022) finds that wood is lost or wasted due to carelessness, useless traditions and even malice. He argues that at least the same amount of wood that is eventually used is lost or wasted, representing significant saving potentials. In addition, his work also proposes several measures to reduce the demand for wood. First, it is stated that buildings were insulated insufficiently. Therefore, improved insulation, for example, with straw or moss, and the use of screed will reduce the heating demand. Moreover, the simple measure of downsizing living rooms is an effective measure to reduce the heating requirement. Second, if chimneys and fireplaces are replaced with closed furnaces, the heat can distribute better and thus heat the room more effectively. In this context, the location of the furnace in the room is very relevant. Third, new inventions, such as tiled stoves, can make a difference. The tiled surfaces of the stove enable the purposeful use of the heat for cooking. In summary, von Carlowitz’ *Sylvicultura Oeconomica* contains the different countermeasures of sowing and planting, the reduction of losses or different types of waste of wood due to, for example, careless or malicious behavior and finally certain technical measures, such as additional insulation and new technologies.

Therefore, the authoring of the *Sylvicultura Oeconomica* can be interpreted as the birth hour of resource efficiency and resource conservation. This brief introduction to sustainability outlines the framework for this dissertation, whose aim is to improve the method of material flow cost accounting (MFCA). MFCA is an effective method for increasing resource efficiency, and it will be introduced and analyzed in Chapter 3. More than 310 years after the publication of the *Sylvicultura Oeconomica* and 38 years after the release of the Brundtland Report, the concept of sustainability has become very important and powerful. It connects and unites, yet at the same time divides families, generations, continents, and political camps.

1.2 Visualization of the Concept of Sustainability: More than Works of Art

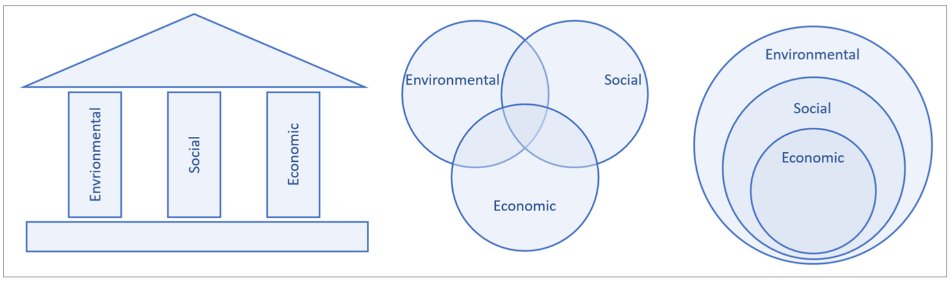
The Brundtland Report has not only functioned as a popular reference regarding the definition of the term, but it has also helped the topic to become part of broader policy discussions. It provided the basis for the 1992 Earth Summit, also called The United Nations Conference on Environment and Development (UNCED) or the Rio Conference, as it took place in Rio de Janeiro (UN, 1992b). Two results of the Earth Summit were the creation of the Commission on Sustainable Development (CSD) and the Agenda 21. While the goal of the CSD was to ensure follow-up activities after the Earth Summit, Agenda 21 was an action plan that was adopted at the Earth Summit by more than 178 member states of the United Nations (UN) (UN, 1992a, 1992b). It aimed at sustainable development on local, national and global levels, requesting every local government to develop its own Agenda 21 (UN, 1992a).

Moreover, the Brundtland Report comprised the idea that sustainable development has three dimensions: environmental, social and economic. In the same year, environmental economist Barbier (1987) published his ideas on the interdependence and necessity of these three dimensions.

Each of these dimensions plays an important role when it comes to defining and pursuing the goal of sustainability. In 1997, Elkington developed the three dimensions further and introduced the concept of the triple bottom line combining the three goals people, planet and profit to the business world. He thus significantly contributed to the popularization of these ideas in the modern globalized world.

There are different illustrations of the different dimensions and Figure 1 includes three of them. The first one (left) has the shape of a house with three pillars and the other two illustrations (middle and right) use circles to express the relationship of the three dimensions to each other. The house is composed of three pillars which together carry the roof. It was gradually developed in the years after the publication of the Brundtland Report by the WCED in 1987, which shaped and popularized the different dimensions of sustainable development (Purvis et al., 2019). The three pillars stand for the social, environmental and economic dimension. This construction can be interpreted in a way that sustainability can only be pursued by respecting and maintaining each of the three pillars to the same extent. If that is not the case, the static of the building is not secured, and it threatens to collapse. The two other illustrations are Venn diagrams, which are characteristically composed of circles that include, exclude or intersect each other (Venn, 1880). The use of a Venn diagram to visualize the different dimensions representing sustainability is ascribed to Barbier (1987). This form of presentation acknowledges that the different dimensions cannot be positioned next to each other since they are intertwined and blend into each other (von Carlowitz, 1713/2022). Therefore, the second illustration consists of three circles. The circles are all of the same size, suggesting that the area in the center—covered by all three circles—complies with sustainability. This expresses the idea that the three dimensions cannot be viewed detached from each other and that their interplay needs to be recognized when pursuing sustainability. The illustration on the right is composed of three circles of different sizes that are embedded in the next bigger circle, respectively. This arrangement proposes that the economy is embedded in society, and society, in turn, is embedded in the environment. A possible interpretation of this version is that the economy depends not only on society, but also on the environment, from which also society is dependent. This dependence needs to be respected when pursuing the goal of sustainability. A further idea based on this illustration is that the larger circle influences and also limits the appearance and characteristics of the circle(s) that lie(s) within it. In contrast to the three other illustrations, this one implies an order of the three dimensions. The concept of sustainability cannot be localized with a certain point in the illustration, but it is rather depicted with the illustration as a whole. A more recent version of the Venn diagram includes a fourth circle, representing, for example, culture (Hawkes, 2001). This extension illustrates that these aspects also play an important role when striving for sustainability.

Figure 1: Graphic illustrations depicting the different dimensions of sustainability



Each of these illustrations adds to the understanding of the meaning of sustainability, albeit none of them is able to capture the meaning of the term sufficiently. The challenge of visualizing the topic of sustainability has been further discussed, for example, by Lozano (2008) or Moir and Carter (2012). That dichotomy can be used as a key idea when striving for a definition: although there is no short and simple definition, there are many useful aspects which can be expressed using words or illustrations, and it is the total amount of them that creates the mosaic picture of sustainability. Finally, perhaps that is what makes the challenge to find a clear-cut definition so demanding: the breadth of the sustainability topic has been keeping this subject matter alive to this day and it will continue to do so in the future.

This section and the preceding Section 1.1 have attempted to point out the sustainability challenge with its multiple dimensions and facets. It requires a combination of the three strategies efficiency, consistency and sufficiency (Pufé, 2017). The present dissertation offers a solution-oriented response to the urgent call of the sustainability challenge. It focuses on the efficiency strategy and pursues an efficient use of natural resources in the manufacturing industry, thus enhancing resource conservation and environmental protection, which in turn are important components of sustainable development.

1.3 The Concept of Resource Efficiency: A Noble, Worthwhile Goal

Generally speaking, efficiency can be described as the ratio between a specific result or benefit and the effort that is required to achieve that result or benefit. Resource efficiency, in particular, divides the necessary resource use by the result or benefit, as the following equation shows (VDI, 2016, p. 12).

$$resource\ efficiency = \frac{benefit_{\ (product,\ function,\ functional\ unit)}}{effort/need_{\ (use\ of\ natural\ resources)}} \tag{1.1}$$

According to (1.1), resource efficiency can be increased by either increasing the nominator, i.e., the benefit, or by decreasing the denominator, i.e., the effort or need. Therefore, the concept of resource efficiency is a promising component of a more sustainable future. Resource efficiency can contribute to the protection of natural resources, and it decreases emissions per good produced. The reduction in emissions, in turn, has positive environmental effects and supports the protection of the environment and the climate.

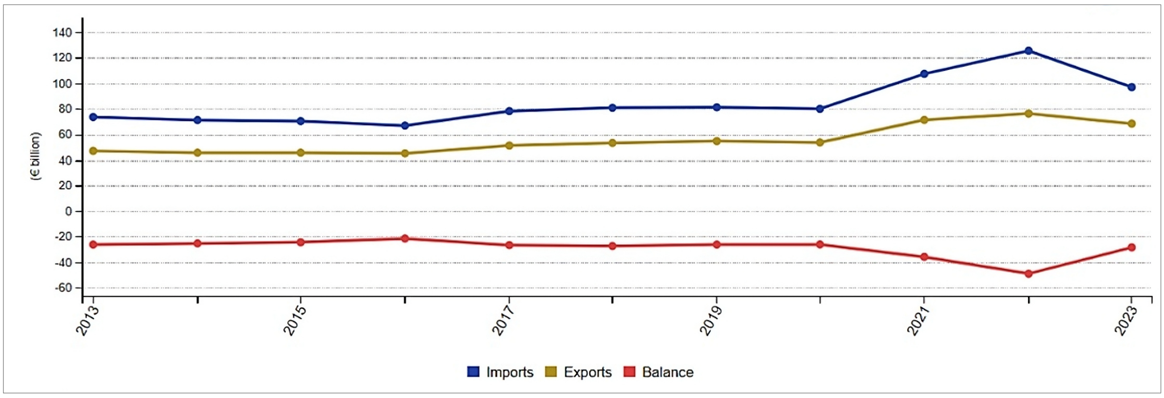
Resource efficiency has been on the political agenda for several years now (European Commission, 2005, 2011, 2020; G7, 2015, 2022). The German Federal Cabinet has passed ProgRess III, which is the third reissue of its national resource efficiency program (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany, BMU, 2020). Moreover, The Association of German Engineers (in German Verein Deutscher Ingenieure, VDI) has developed and published three guidelines on the topic of resource efficiency (VDI, 2016, 2018, 2022). In conclusion, the topic of resource efficiency is of high relevance both for politics and economic actors, as it combines and equally pursues economic and ecological goals.

1.4 Motivation and Aim of This Work: The Reduction of Raw Material Dependence

Having introduced the concepts of sustainability and resource efficiency, the motivation and objective of this work will be outlined. In *Sylvicultura Oeconomica*, von Carlowitz (1713/2022) already called a country “fortunate”[1] (p. 54) that is not dependent on imports. In light of today’s globalized world—despite the growing geopolitical tensions—this seems unrealistic and impossible. Furthermore, international trade is an essential pillar of economic and also human development, and it can also foster freedom and peace. Therefore, von Carlowitz’ statement should be questioned in hindsight.

Nevertheless, for this very reason, the main motivation lies in the dependence on raw material imports, which is the case for literally all countries around the world, and which fuels their economies. Taking a look at the data provided by the European Union (EU) (European Commission, 2024), the following Figure 2 describes this situation. While the share of exports of the raw material category containing metals, minerals and rubber totaled 38% (based on monetary values) in 2023, the imports of this category totaled 49% in the same year. Looking at the raw material trade balance of the EU, it has been negative for more than two decades. The data for 2022 reveals the new maximum import value of 125.3 B EUR, resulting in the trade balance of –49.1 B EUR. This is the largest deficit in the period between 2013 and 2023.

Figure 2: EU trade in raw materials 2013–2023 (Eurostat, 2024)



The data for the EU member state Germany confirms this statement. The Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) reported the country’s raw material imports and exports in 2022 and 2023 of the physical and monetary values that are comprised in the following Table 1 and Table 2.

[1] Own translation, original in German: “glücklich” (von Carlowitz, 1713/2022, p. 54)

Table 1: Raw material imports and exports of Germany 2022 and 2023, physical values (BGR, 2024, p. 22)

Trade category	Imports		Exports		Trade balance*	
	2022	2023	2022	2023	2022	2023
	M t	*M t*	*M t*	*M t*	*M t*	*M t*
Energy	236.5	200.7	45.4	38.0	–191.1	–162.7
Metals	79.5	73.9	42.4	41.5	–37.1	–32.4
of which recycling metals	7.3	6.4	12.7	12.5	5.4	6.1
Nonmetals	26.1	23.8	42.4	39.1	16.3	15.3
Total	342.0	298.4	130.1	118.6	–211.9	–179.8

* Own calculations.

Table 2: Raw material imports and exports of Germany 2022 and 2023, monetary values (BGR, 2024, p. 21)

Trade category	Imports		Exports		Trade balance*	
	2022	2023	2022	2023	2022	2023
	B EUR	*B EUR*	*B EUR*	*B EUR*	*B EUR*	*B EUR*
Energy	184.6	118.3	41.5	29.3	–143.1	–89.0
Metals	122.6	94.0	90.3	81.2	–32.3	–12.8
of which recycling metals	16.8	13.4	12.9	10.7	–3.9	–2.7
Nonmetals	4.6	3.9	3.5	3.7	–1.1	–0.2
Total	311.7	216.2	135.3	114.2	–176.4	–102.0

* Own calculations.

The values of the imports exceed those of exports for the categories *Energy* and *Metals* in both physical and monetary units. For example, in both years, the mass of energy imports exceeds the corresponding exports by more than factor four and the mass of metal imports is almost twice the mass of metal exports. The two categories *Nonmetals* and *Recycling metals* are the only ones in which mass values of exports exceed the import values (cf. Table 1). However, measured in the monetary unit EUR, import values exceed export values again, and the trade balances are negative for all trade categories (cf. Table 2). The comparison of the figures of 2023 with those of 2022 shows that the total amount of imports has decreased by 12.7% or 43.6 M t in physical terms and 30.6% or 95.5 M t in monetary terms. The total amount of exports also decreased in 2023 compared to 2022 by 11.5 M t (8.8%) and 21.1 B EUR (15.6%), respectively. Although the trade balance of recycling metals is positive in both years, both imports and exports have reduced in physical and monetary terms in that period. This brief analysis shows the high import dependence of the German economy including the metals processing industry and energy sector. It represents a strong argument for the efficient use and reuse of raw materials in general and metallic and energy resources in particular.

Over the last decades, global absolute resource demand has been increasing. According to the International Resource Panel (IRP) of the UN, global material extraction for the four main material categories biomass, fossil fuels, metal ores and non-metallic minerals has tripled from below 30 B tons in 1970 to more than 90 B tons in 2015 (IRP, 2019; based on UNEP & IRP, 2018). Moreover, the IRP states that “material efficiency is not systematically included in most mitigation scenarios or climate policies. As this report shows, studies of material-related policies often focus on waste management rather than GHG [greenhouse gas] emissions" (IRP, 2020, p. 14). The focus of manufacturing processes lies on the output, according to the IRP (2020).

However, the inputs that are required to produce the desired products are becoming increasingly important due to global economic interdependence and the growing requirements regarding sustainability criteria. According to the German Statistical Office, the share of material costs in the total revenue of the companies belonging to the German manufacturing industry was 54.7% in 2020 (Federal Statistical Office of Germany, 2023). Considering this share of more than half of the total revenue, an improvement of a few percent will reduce a company's costs and lead to a positive effect on its profitability. Therefore, the saving potentials based on resources should still be high in the industry. Finally, in light of the global supply chains and their vulnerability, which, for example, became a problem during the coronavirus disease 2019 (COVID-19) pandemic, resource efficiency is an effective and therefore necessary strategy. It decreases the economy's dependence on imports and its environmental impact regarding greenhouse gas (GHG) emissions, thus increasing the future sustainability of the country's manufacturing industry.

Due to the described and illustrated raw material dependence of the EU's and Germany's economy, the aim is to increase the manufacturing industries' resource efficiency in order to reduce the raw material dependence. To achieve this, this dissertation strives to improve the method of MFCA, which in turn is able to increase the resource efficiency of a manufacturing process. MFCA is a method that can increase the resource efficiency of a production process by either decreasing its resource demand or by increasing its amount of output. This leads to positive effects that reduce the physical, environmental and monetary values per unit of output of the process under analysis, as the previous Section 1.3 explained.

This dissertation is embedded in the field of industrial ecology. Industrial ecology is a research discipline that analyzes manufacturing processes and product designs in order to support companies regarding environmentally informed decisions (Lifset & Graedel, 2002). Furthermore, industrial ecology argues that the industry emits a large share of environmental emissions and consequently, companies are an important factor with regard to the reduction of environmental emissions, e.g., through technological expertise. Lifset and Graedel (2002) define three types of ecosystems: type I represents linear material flows and unlimited waste, type II represents quasi-cyclic material flows leading to limited waste and type III contains cyclic material flows. Type III requires merely energy as additional input and it does not generate any waste at all (Lifset & Graedel, 2002). Just like MFCA, industrial ecology ascribes a significant role to the industry as a whole and to individual companies in the pursuit of a type III ecosystem, representing the basis for a circular economy, whose importance has been growing rapidly and which is also debated in research literature (e.g., Corvellec et al., 2022; Geissdoerfer et al., 2017; Kirchherr et al., 2017). Being a method of resource efficiency, MFCA is also an effective tool to pursue the goal of dematerialization, a reduction of resource use and environmental emissions as a result of production processes and economic activities.

The application of MFCA in industrial contexts has remained rather low since its development in Germany and Japan. This is rooted in methodological improvement potentials, as Chapter 3 will address. The objective is to bestow more industry- and practice-orientation on the method with the help of cost accounting theory. A reduction of material and energy inputs of a production process at the same time enables the reduction of costs and environmental emissions related to these inputs. Thereby, MFCA builds a bridge between the economic and ecological dimension of sustainability and—in a broader sense—also addresses the social dimension because an increase in resource efficiency paves the way for a more just distribution of natural resources throughout the world and between generations.

At the point of writing, there is little research and literature focusing on German cost accounting theory on a conceptual level with some exceptions (Friedl et al., 2009; Krumwiede, 2005; Krumwiede & Suessmair, 2008; Sharman, 2003). Drury (2012) generally confirms this observation and argues that cost and management accounting publications are either too practice-oriented, hence losing sight of the bigger picture, or, if that is not the case, the publications are purely conceptual and normative, focusing on management accounting, i.e., theorizing about information for decision-making, planning and control. Therefore, the objective of this research is to improve MFCA by blending and enriching the method with German cost accounting theory. Moreover, this dissertation is written in the English language to increase the reach and impact of this research topic. The meaning of the work of the German cost accounting scholars Wolfgang Kilger and Paul Riebel—particularly Riebel's identity principle as cornerstone of his work—and the topic of language barriers should not be underestimated (J. Weber & Weißenberger, 1996). Therefore, this thesis aims to decrease language barriers that may be hurdles in the way of progress. It introduces German accounting theory to the international scientific community in Chapter 2, hence providing food for thought on how to approach the sustainability challenge from a different corporate perspective.

1.5 Research Questions and Method

After the thematic introduction, this dissertation will address the following research questions in its further course:

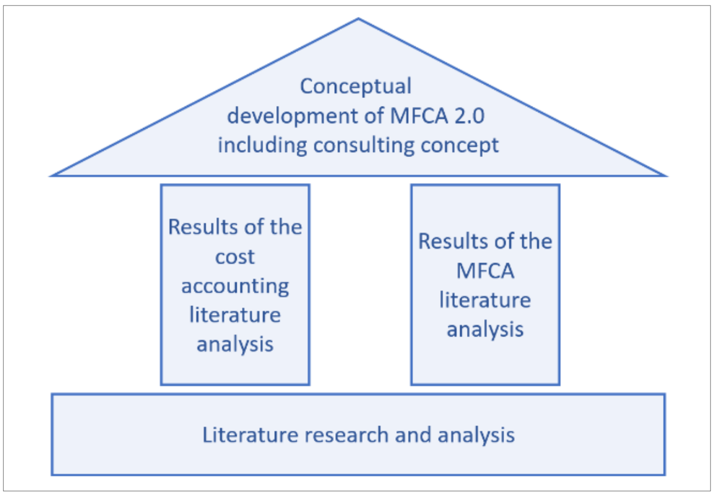
- What can be learned from the cost accounting debate of the 20th century for the MFCA method? (*Research Question 1*)
    - How did Riebel and Kilger differentiate their approaches from the current state of cost accounting at that time? (*Research Question 1.1*)
    - How did Riebel and Kilger refine their approaches over time? (*Research Question 1.2*)
    - What is the meaning of the *identity principle* and how can it be transferred to the method of MFCA? (*Research Question 1.3*)
- How can the MFCA method be adapted in order to make it more practice-oriented and thus practice-relevant for the manufacturing industry? (*Research Question 2*)
    - How can the MFCA method evaluate loss reductions that are technically feasible and below 100%? (*Research Question 2.1*)
    - How can the effect and corresponding saving potential of multiple simultaneous material loss reductions be evaluated? (*Research Question 2.2*)
    - How can the evaluation of material loops in the system under analysis be included in the MFCA method? (*Research Question 2.3*)
    - What does an adequate consulting concept look like that supports the implementation of the method and that encourages its continuous use? (*Research Question 2.4*)

This dissertation was written in English, and the language is a central feature of this work. The fact that the research questions are formulated and answered in English adds additional value to the results. This is because both the development of the MFCA method and the debate on cost accounting of the past century primarily took place in Germany and in the German language. Until today, there is little research on the German cost accounting debate which was led by the two professors and scholars Kilger and Riebel. Their works will be analyzed mainly in Chapter 2.

In the context of these research questions, the following methodological approach of conceptual scientific research was selected. In order to develop an adequate understanding of the subjects, the relevant literature was studied thoroughly. This comprised the review and analysis of cost accounting literature of the 20th century, with brief digressions to sources dating even further back to the beginnings of the discipline in the previous centuries (Chapter 2). The analyses focus on the meaning, function and goal of cost accounting approaches and results, and Kilger (1993) and Riebel (1994b) both came up with novel and unknown ideas and approaches at their time, respectively. These developments are analyzed with regard to Research Questions 1.1, 1.2 and 1.3 and purposefully summarized in the course of this dissertation.

The described cost accounting literature analysis represents one pillar of this research; the second pillar is based on the method of MFCA. Chapter 3 reviews and analyzes the method with regard to its current level of development and practicability. Moreover, methodological improvement potentials are derived as a result of the analysis. Based on these conceptual pillars and drawing on the results of these analyses, a new and integrative MFCA approach called *MFCA 2.0* will be developed. The approach focuses on the manufacturing industry as it requires large amounts of materials and energy for its processes. Due to increasing costs and rising requirements regarding environmental measures, the manufacturing industry needs a more efficient use of them. The concept of the new method is the result of this methodological approach, and it is mainly based on an element that turned out to be a game changer in cost accounting history. Since the advancement of the method is highly practice-oriented, it will be complemented with a consulting concept for companies that combines theoretical and practical ideas. It is also the result of the literature analysis, and it supports the method's implementation in practice. In summary, MFCA 2.0 and the consulting concept address the aspects of the method's current state of development that hamper its implementation in practice. Figure 3 summarizes the methodological approach of this research.

Figure 3: Methodological approach of the research



1.6 Structure of This Dissertation

This dissertation is structured in seven chapters. Chapter 1 outlines the thematic background by introducing the concepts of sustainability and resource efficiency. After the outline, the motivation and aim of this work are described. They are both anchored in the topic of raw materials, and they focus on the analysis and improvement of the MFCA method. The MFCA method aims at a more efficient use of raw materials in a production process, i.e., an increase in resource efficiency. This provides the basis for the derivation of the research questions, which then provide guidance for the following chapters.

Chapter 2 lays the theoretical foundation for the aspired methodological improvement by providing a thorough and yet concise overview of the beginnings, evolution and purpose of the cost accounting discipline. This chapter focuses on the works and ideas of Kilger (1993) and Riebel (1994b) who both made significant contributions to the cost accounting discipline. They led a meaningful scientific debate in the second half of the 20th century, which was analyzed in Chapter 2 to answer Research Question 1 including the subordinated Research Questions 1.1, 1.2 and 1.3.

Chapter 3 introduces the MFCA method and briefly outlines its current status in research and practice. This includes the origin of the method and its standardization by the International Organization for Standardization (ISO). Moreover, Chapter 3 comprises the method's advantages as well as aspects of the method that could be refined and improved regarding its usability in practice. The end of this chapter addresses Research Question 2 and makes preparations for answering the subordinated Research Questions 2.1 to 2.4.

Chapter 4 and Chapter 5 represent the heart of this dissertation. Research Questions 2.1, 2.2 and 2.3 are the focus of Chapter 4. It introduces the improved scenario-based approach MFCA 2.0 and it illustrates the new operating principle with different application examples for loss reductions below 100%, for multiple simultaneous loss reductions, and for material loops. Thus, it gradually answers the three research questions. In this chapter, the specific saving potential for each application example is determined following the scenario-based algorithms of MFCA 2.0. Chapter 5 contains the consulting concept which Research Question 2.4 requests. The chapter considers a variety of practice-oriented aspects that are relevant for the successful implementation of the MFCA 2.0 method. Another important aspect, which the chapter addresses, is the continuous use of the method in a corporate context.

Chapter 6 reflects this work and its research results. It takes up the cost accounting debate that was discussed in Chapter 2 and contextualizes the newly developed method MFCA 2.0 and the consulting concept. This chapter includes challenges, limitations and additional research demand based on the research results, thereby providing a critical review. Moreover, it puts the work in the overall context of the sustainability challenge and the object of sustainable development.

Finally, Chapter 7 summarizes and concludes the dissertation. It recapitulates the main results and puts them into context by referring to historical aspects of cost accounting. Moreover, the chapter works out MFCA 2.0's contribution to an increase in resource efficiency and views the method in light of the sustainability challenge. It closes with a call for action.

2 Theoretical Background of Cost Accounting: Making the Numbers Count

Suppose one of you wants to build a tower. Won't you first sit down and estimate the cost to see if you have enough money to complete it?—Luke 14:28

Cost accounting has a long tradition and an eventful history. The working group for internal cost accounting of the Schmalenbach Society responds to the question about today's relevance of historical cost accounting classics with the argument of technological progress: Due to limited computing power and electronic data storage, many approaches had to stay theoretical constructs (Arbeitskreis Internes Rechnungswesen der Schmalenbach-Gesellschaft für Betriebswirtschaft e.V., 2017). To pave the way for the further development and improvement of cost accounting, it is necessary to understand where it comes from, what questions have been asked already and how they have been attempted to be answered. Therefore, it is a promising endeavor to reconsider theories of the past and to look for new ideas and impulses for today's research and practice.

2.1 The Purpose of Cost Accounting in Practice

The purpose of cost accounting is company-internal because it addresses a company's managers and employees as part of internal accounting (Horsch, 2023). Internal accounting is a company's centralized information system and cost accounting aims to provide information for the company's operative management. Moreover, cost accounting produces rational information for operational decision-making. These decisions can concern the following questions (Horsch, 2023):

- Should a specific order be accepted at all?
- What rationalization measures should be implemented?
- Shall the company continue to produce a certain product?
- What is the answer to a certain make-or-buy decision?
- What is the best production process for a specific product order?

There are multiple ways how to carry out cost accounting because many different forms of cost accounting have been developed over time. According to cost accounting scholar Kilger, the following four reasons have led to this diverse development (Kilger, 1993). First, cost accounting used to be subject to the requirements and problems of executive management over time, leading to strong impulses for the development of the discipline. The requirements of executive management have increased in terms of quantity and quality over time. Second, the interplay of cost accounting and computer technology has created new possibilities and new ideas for the theory and practice of cost accounting, offering different options for action. Third, an important factor is the company's standard of knowledge on the one hand and the educational training in schools and other institutions on the other hand. The knowledge of students and employees is an important direction arrow from theory to practice. Fourth, the organizational and technological structure of a company determine the level of complexity and hence also determine how cost accounting is implemented (Kilger, 1993). Although the evolution of cost accounting has brought about many new opinions, forms and directions, Kilger (1993) argues that there was a coherent trend because it was a necessary development over the decades. This coherent trend led from different forms dealing with actual costs to normal costing and finally to absorption costing (Kilger, 1993).

2.2 The Evolution of Cost Accounting

Cost accounting has a long tradition, and its beginnings are rooted in Italy in the 15th and 16th century (Mattessich, 2003). In the USA, it was Jerome Lee Nicholson who made significant contributions to cost accounting by illustrating the meaning of *cost centers* and the calculation of department-specific profits using machine hours. Furthermore, he organized the precursor of today's Institute of Management Accountants (IMA) (Mattessich, 2003). The German Eugen Schmalenbach is the person that is said to have called cost accounting into life in German-speaking countries (Mattessich, 2003). The German term *Kostenrechnung* (cost accounting) is older than the term *Betriebswirtschaftslehre* (business administration) (Arbeitskreis Internes Rechnungswesen der Schmalenbach-Gesellschaft für Betriebswirtschaft e.V., 2017). It took many more years until German cost accounting was characterized by Kilger and Riebel whose academic debate on cost accounting, their theories and their motivations will be described in this chapter.

2.2.1 An Overview of the History of Cost Accounting

The discipline of cost accounting developed over many decades, and it represents a large subject area. Notwithstanding, scholar Kilger delved into cost accounting history, gathered many literature sources and information pieces and published this in his main work in 1961 for the first time. As the preface of the eighth edition explains, the historical explanations were shortened, and marginal costing theories were included (Kilger, 1993). It is a comprehensive and detailed work because it comprises a large number of bibliographical references, sources and comments in the form of footnotes. Inquisitive readers may understand this as invite to read the work themselves and to dive deeper into the history of cost accounting. Moreover, Kilger oftentimes refers to literature reviews in the cost accounting field such as the ones from Solomons (1952) or K. Weber (1960a), who both covered the genesis of *standard cost accounting* in the US. In Germany, cost accounting has a long history of over one century. It was Schmalenbach who started to publish his ideas on the functions of cost accounting in the beginning of the 20th century, for example, in the article "Die Technik der Produktionskostenermittlung" (Schmalenbach, 1907/1908), which can be translated as "Technique of the Determination of Production Costs" [own translation].

In summary, the overview Kilger provided is a remarkable contribution and service to this research field, and it offers a solid basis for the following historical overview, which in turn is the starting point of this dissertation.

2.2.1.1 Cost Accounting With Actual Costs

Actual cost accounting was a stage of development in the history of cost accounting that aimed to quantify the costs that actually accrued (Kilger, 1993). It takes a past perspective and uses so-called factor prices and factor quantities to calculate the effective or actual costs. Although it is a straightforward approach, its implementation requires assumptions and estimations, and not all costs that accrue within a given period of time can be quantified accurately. As a result, some cost components in actual cost accounting are planned, average or normalized costs to a certain extent (Kilger, 1993). The main characteristic of actual cost accounting is the *principle of passing on costs* to the different cost carriers. This form of cost accounting is not able to identify deviations and hence, it is not able to control costs. Furthermore, actual cost accounting is a slow form of cost accounting because it demands monthly updates of average prices, cost rates and calculation values to execute the principle of passing costs on (Kilger, 1993).

Due to these time-consuming procedures, the preference of average prices and later fixed internal prices over actual prices were obvious steps to implement actual cost accounting in a corporate context. Basically, average prices represent normalized costs, and fixed internal prices represent standardized values, which were both of high relevance for the further development of cost accounting. Moreover, the principle of passing costs on was abandoned to some extent since it focuses on the processing of actual costs only (Kilger, 1993). At the same time, this was an important step towards cost control because the elimination of price fluctuations enables the control of consumption quantities (Kilger, 1993). This allowed the calculation of the *additional* consumption volumes of direct materials based on the difference of the target quantity and the actual quantity. These differences had to be documented with a special material receipt so that the actual costs can be analyzed with the help of the three categories planned direct material costs, direct material quantity differences and price variances. This approach represented a simple form of economic efficiency control of *direct* material quantities and *direct* material costs for the first time in the history of cost accounting and business management (Kilger, 1993).

Kilger (1993) summarizes that the practice of actual cost accounting deviated from its initial form over the years and that there are tendencies towards normal and planned costs. Nevertheless, he concludes, actual cost accounting is originally characterized by the principle of passing costs on and the monthly update of actual cost rates (Kilger, 1993).

2.2.1.2 Cost Accounting With Normal Costs

Normal costing simplified and accelerated the practice of cost accounting, which had been coined by actual costs. The cost rates of normal costing emerged from the idea that cyclical fluctuations cancel out over time due to, for example, seasonal variations (Kilger, 1993). This was an important finding, considering the aforementioned advantage of economic efficiency control. For this reason, average values were calculated based on actual costs and capacity utilization rates of past periods, leading to *normal cost rates*, which were used for a period of at least one year (Kilger, 1993). This step accelerated the practice of accounting for the current period and increased its practicability significantly (A. Müller, 1938, 1952).

Positive and negative differences between actual and normal costs, i.e., surpluses and deficits, for the cost centers could now be determined (Kilger, 1993). However, these differences were mainly caused by changes in capacity utilization over time, making it difficult to identify and analyze other causes (Kilger, 1993). To enable this, the costs were differentiated between fixed and proportional costs, and the proportional costs were adjusted depending on the changes in capacity utilization. This important step that aims to take changes in capacity utilization rates into account when working with proportional costs led to the affix *flexible normal costing* (Kilger, 1993). If changes in capacity utilization rates were not considered, the cost accounting approach was termed *rigid normal costing* (Kilger, 1993).

A. Müller (e.g., 1938) and Wolter (1948) were the two most important cost accounting researchers that described *flexible normal costing* in the literature. However, Kilger (1993) concludes in his overview, it was difficult for this cost accounting method to gain currency due to its demanding level of complexity. Nevertheless, flexible normal costing was the first cost accounting method that allowed to at least partially control costs on the basis of cost centers (Kilger, 1993). The idea and goal to control costs was developed in 1933 by A. Müller in his dissertation titled *The Isolation of Influences on the Cost Price in the Ironworks Industry* [own translation][2]. In those years, the motivation for cost control in the iron industry was twofold: there was strong competition between the ironworks companies, and these companies were very large entities, making it difficult to oversee their processes and the financial conditions behind them (A. Müller, 1933). Later on, A. Müller and Rummel recognized the dependence of costs on their influencing factors and suggested the standardization of costs.

However, it took many more years to form these ideas and develop *flexible standard costing*, as will be shown in the following (Kilger, 1993). What may seem logical and trivial to a certain extent in hindsight, was pioneering work at the time these ideas and instructions were published. Originating from this groundwork, the cost accounting systems based on actual costs and normal costs were extended with values of predefined working time and later also with quantities of other necessary production factors. This represents the idea of standard costing, which is the focus of Paragraph 2.2.1.3.

2.2.1.3 Cost Accounting with Planned Costs, Also Known as Standard Costing

After the end of the First World War (WWI), the economic and political circumstances had changed significantly, offering opportunities and risks alike. The years of short-sighted crisis management were meant to be over. These changes were the reason why many companies—first in the US and then in many European countries—in the years after the war decided to invest more time and effort in corporate and operational planning activities (Kilger, 1993). Therefore, the interest in planning and consequently also in budgeting activities grew (Kilger, 1993).

With the development and introduction of the piecework wage, work science made another important step towards planned costs in the field of cost accounting. Just like working time was standardized based on the workflows to be carried out during that time, other production factors could be standardized based on the production processes. Following this advancement, the science of operational management moved towards material quantity specifications. These standardized production factors were then turned into standardized and planned costs for the different cost centers (Kilger, 1993). Standard costing is characterized by the independence of the values of planned costs for a certain planning period from actual costs of the past (Kilger, 1993).

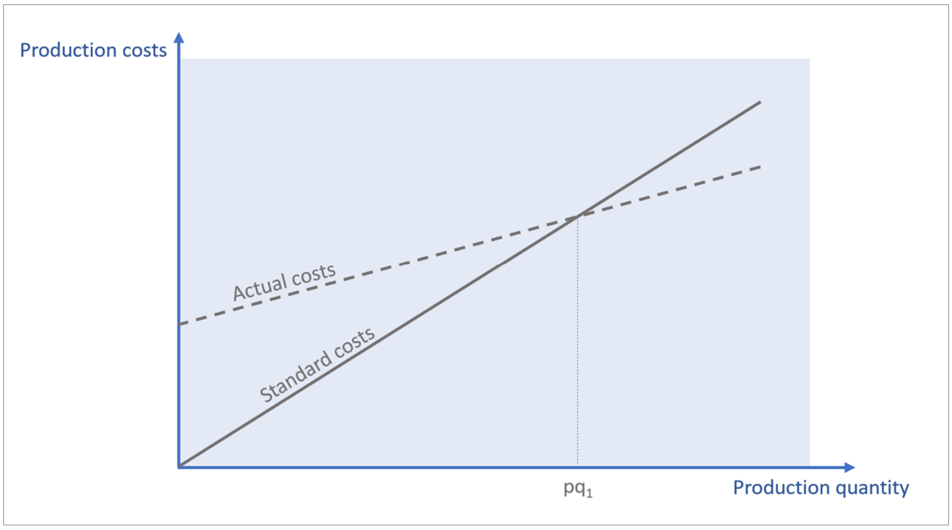
When practicing *standard costing*, i.e., planning the costs that are accounted for via cost centers, four steps are necessary. First of all, each cost center requires at least one reference parameter which relates to these costs and which can be measured in physical units such as hours or kilograms (Kilger, 1993). Second, the average capacity utilization rate needs to be quantified, which relates to the desired amount of output (Kilger, 1993). In this step, the operational planning department of the company should be involved (Kilger, 1993). Third, the corresponding values of the production factors are calculated based on consumption analyses, technical calculations, estimations and surveys (Kilger, 1993). The fourth and last step includes the multiplication of all the production factors with wage rates and fixed prices (Kilger, 1993). As a result, all cost centers

[2] Own translation, original in German: "Die Isolierung der Einflüsse auf die Selbstkosten im Eisenhüttenwesen" (A. Müller, 1933)

are equipped with standard costs for the different cost types. This represents a full costing approach which does not differentiate fixed costs from variable costs (Kilger, 1993).

Due to the assumption of a certain production quantity and hence capacity utilization, differences between planned costs and actual costs can occur. These differences cannot be analyzed and understood because the difference has two causes: the change of variable costs due to the changed quantity and cost deviations due to other factors such as inefficiencies (Kilger, 1993). The following Figure 4 visualizes this problem. The costs (y-axis) increase with the growing production quantity in both cases. However, standard costs do not separate fixed costs and suppose that they develop linear, which is why the cost curve cuts the zero point of the diagram. The dashed—because unknown—line depicts the actual costs. It has a smaller gradient than the standard cost curve because it separates fixed costs that accrue regardless of the production quantity. The diagram shows that these cost curves only correspond with each other at production quantity 1 (pq_1). The missing distinction between fixed and variable costs impedes the cost analysis in the case that the planned production quantity changes (Kilger, 1993). The cost difference cannot be analyzed regarding changes in the production quantity and inefficiencies, respectively. In 1949, Auler reviewed German standard costing and concluded that this rigid approach does not allow a cause analysis of arising surpluses or deficits. These can be caused either by a capacity utilization rate that is too low, or by an additional consumption of production factors above planned quantities, or by both (Auler, 1949). Despite the rigidity of this version of standard costing, it provided an important basis for cost analyses. Nevertheless, it required further ideas to provide a cost accounting method that generates accurate information for corporate cost control.

Figure 4: Cost function of standard costs and actual costs (Adapted from Kilger, 1993, p. 38)



The idea of standard costing most likely appeared in the US for the first time (Kilger, 1993). It was the engineer and consultant Gantt who developed many ideas on economic planning and who also invented a management tool now known as the *Gantt chart*, which was published by Clark in 1922 after Gantt's death in 1918. Hence, the idea of *planned cost accounting* was born. In 1926, de Haas presented the US-American innovation of standard costs to an international audience of an accounting conference in the city of Amsterdam (Haas, 1927). The presentation was titled "Standard Costs as a Basis of Management and Industrial Control". De Haas argued that if cost accounting shall play a leading role, values based on historical data such as average and normal values were not expedient. Instead, he presented standard costing as the method of choice in order to execute control over cost and to analyze cost variances (Kilger, 1993). The US-American developments in the field of cost accounting motivated German scholars to also develop these cost accounting methods further.

The German term *Plankostenrechnung* was coined by Lehmann (1925), who first suggested *planmäßige Kosten*, i.e., *planned costs*, and later used the German equivalent for *standard costing*. The first extensive work that was written and published in German was *Rechnungswesen und technischer Betrieb. Die Grundlagen der Plankostenrechnung* (in English *Accounting and technical operations. The foundations of standard costing*) by Lorch and Sommer (1929). US-American cost accounting research had developed the concept of planned costs instead of normal costs earlier than German scholars, but it had a slightly different focus: The term *standard costs* implies "[…] planned costs per product unit, in particular the planned production costs […]" [own translation][3] (Matz, 1964, p. 103). The reason laid in the fact that German planned cost accounting originated from cost center accounting, while American *standard costing* had its origins in *cost unit accounting* (Kilger, 1993). Due to this slight difference, the German cost accounting community preferred the designation *planned costs* ("Plankosten" in German) over *standard costs*. Although the explanation of these developments would exceed the scope of this thesis, their outcome should not be neglected because of the linguistic aspects that cost accounting history has brought forth.

The growing interest in planning activities generated interest in the topic of operational budgeting as an instrument to refer the planning activities to the different responsible departments. The popularity of the topic generated a plethora of scientific publications and in 1930, an international conference on the topic of budgeting took place in Geneva. Budgeting was understood and implemented as a method for operations management. Hence, it fueled the introduction of planning and budgeting activities into the cost accounting department in order to control costs effectively (Kilger, 1993; Mizoguchi, 1972). As it is often the case, it was not the first time that the idea of budgeting was thought. Instead, as Käfer (1955) has proved, it had already existed for about 100 years before, for example, in Germany and France. Indeed, it had been documented at the beginning of the 19th century already. However, the decisive factor that led to the breakthrough and implementation was the economic downturn. Once the economy began to flourish, the interest in budgeting activities decreased again. The years during the Second World War (WWII) and their wartime economy reduced the interest in such forward-looking methods even further (Kilger, 1993).

2.2.1.4 Cost Control Based on Flexible Standard Costing

What turned (*rigid*) standard costing into *flexible* standard costing is the consideration of current capacity utilization rates and the integration of these into the quantification of different cost components (Kilger, 1993). Flexible standard costing defines the cost components with the help of a function of the current capacity utilization, respectively, and this represents another quantum leap in the history of cost accounting because costs could from then on be calculated more precisely (Kilger, 1993). It had become an integral part of US-American cost accounting in the 1930s already (Kilger, 1993; Plaut, 1953). The decisive task was to differentiate fixed costs from proportional costs. Based on this differentiation, fix costs are assumed to be unchanging and proportional costs

[3] Own translation, original in German: "[…] pro Erzeugniseinheit geplanten Kosten, insbesondere die pro Erzeugniseinheit geplanten Herstellungskosten […]" (Matz, 1964, p. 103)

are assumed to change proportionally to the reference parameter *capacity utilization*. As a consequence, cost differences, i.e., surpluses or deficits, can be led back to both changes in the actual capacity utilization rate compared to the planned value, and changes in the actual consumption quantities compared to the planned quantities (Kilger, 1993).

Despite this important refinement, this stage of development of cost accounting was not successful in practice. One important reason laid in the challenge to find accurate reference parameters, for example, due to the individuality of orders or series production, causing misleading results, which Kiebel (1940) had recognized and published many years before already. To overcome these problems, cost centers and reference parameters had to be refined and reduced in scope, which can be achieved through the reduction of machine group sizes and workplaces. The downside of these corrective measures impeded account assignment, hindering its implementation in practice (Kilger, 1976).

Interestingly, the approach of flexible standard costing was revived in 1950. A decisive factor were the activities of a working group that organized itself as an association ("eingetragener Verein" in Germany) for the promotion of the topic of corporate planning. It was named AGPLAN and it offered conferences, seminars and publications in written form to make the topic and its new features known (Kilger, 1993). It was also the association AGPLAN that later provided a platform for Plaut to disseminate and teach a new accounting system, focusing on direct costs, to his target audience (Kilger, 1993).

The review of the development of flexible standard costing reveals three important aspects. First of all, it was the first form of cost accounting that provided information to enable effective cost control (Kilger, 1993). Second, it turned out that cost accounting is most effective when it is not an add-on of corporate management, but an integral part of corporate planning, communication and collaboration with other planning processes (Käfer, 1964). Third, it was not the content alone that guided the development of the method, but also additional activities arranged and carried out by the institution AGPLAN (Kilger, 1993). The association provided a platform for new ideas, exchange and discussion, but also for education and training, which contributed significantly to the positive publicity of the research field.

2.2.2 Absorption Costing: Critique of the Full Costing Approach

Actual costing, normal costing and standard costing all fall under the category of absorption costing, which is the common denominator of the three different approaches. Absorption costing, also called full costing (*Vollkostenrechnung* in German), allocates *all* costs to the different cost carriers (Riebel, 1994b). It was the prevalent management accounting system in Germany in the 1950s and 1960s, its origins dating back to the beginning of the 20th century (J. Weber & Weißenberger, 1996).

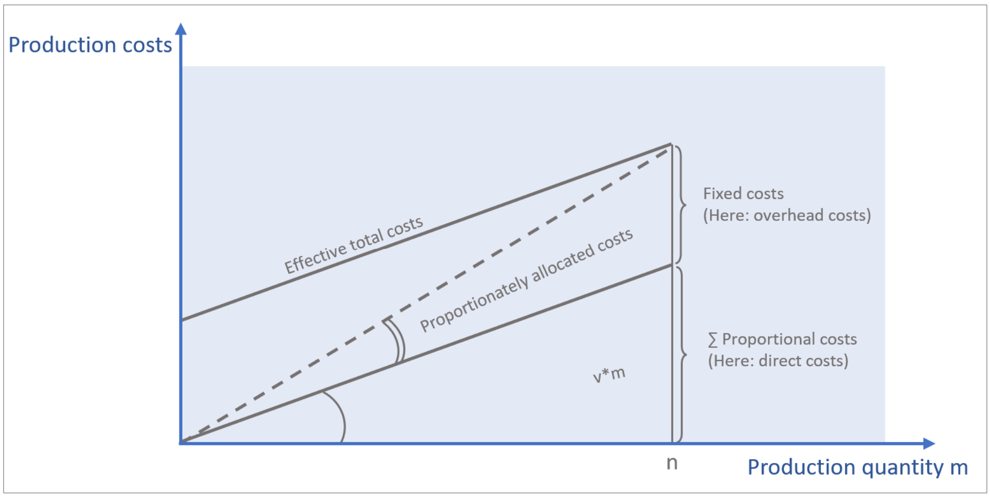
Absorption costing does not keep proportional and fixed costs separate from each other because it allocates overhead to the cost carriers. The first step usually applies quantity-based allocation keys to allocate the costs to the different cost centers. The second step then requires value-based allocation keys to allocate the costs to the cost carriers (J. Weber & Weißenberger, 1996). Thereby, the cost carriers are analyzed in isolation, calculating both fixed and proportional costs per unit or production order (Riebel, 1994b). Based on this procedure, Riebel recommends the designation "Gemeinkostenaufteilungsrechnung"—"overhead cost distribution accounting" [own translation] in English—because the terms *full costing* ("Vollkostenrechnung" in German) and *rolling over accounting* ("Kostenüberwälzungsrechnung" in German) or *passing on accounting* were also used to describe other accounting methods at that time, which these terms describe more appropriately in his opinion (Riebel, 1994b).

Although the proportionalization of fixed costs had been practiced long before the emergence of flexible standard costing, it became more manifest then due to the differentiation between fixed and proportional costs in flexible standard costing. Fixed costs were usually treated as overhead costs since their amount does not depend on the production volume. While proportional costs vary with the production volume and can be changed in the short term, fixed costs can only be changed in a longer term, and they require management decisions such as increases or decreases in production capacities. This kind of decisions requires investment calculations and not an absorption costing approach (Kilger, 1993). That is also the reason why fixed costs are not relevant for short-term decisions. With regard to flexible standard costing allocating fixed costs, this represents the main critique. Moreover, this is not in line with the principle of causation because the provision of production capacities is time-dependent (Kilger, 1993). Fixed costs are the result of production factors that cannot be postponed and as a consequence, Kilger defines fixed costs as *period costs*. In Anglo-American literature, fixed costs are also called *period costs* or *readiness to serve costs* (Kilger, 1993).

Furthermore, there are *genuine* and *non-genuine* overhead costs. Genuine overhead costs with regard to the cost carriers are costs that cannot be quantified for an individual cost carrier. This is, for example, the case for all costs of a joint production process yielding more than one product. Being trained as a chemist, this represented a daily and important challenge to Riebel, and he decided to take on this challenge from a cost perspective (Riebel, 1994b). Non-genuine overhead costs are defined as follows: They can indeed be measured or quantified correctly in practice, but this seems too time-consuming and costly. Therefore, non-genuine overhead costs are treated as if they were overhead (Riebel, 1994b).

Riebel structured his critique of traditional absorption costing as follows. The proportionalization of fixed costs, which is independent from the type(s) of product and the output quantity, enables the mixing with proportional costs, leading to the wrong conclusion that the fixed costs increase with every additional production unit. Moreover, the allocation of fixed costs between multiple products is problematic because—following the first point of criticism—they are wrongly transferred in the form of proportional costs. As a consequence, this suggests that the fixed costs are caused by a single product and that they grow with every additional production unit (Riebel, 1994b). This cost accounting procedure is only possible with the help of allocation keys which Riebel characterizes as arbitrary and incorrect because fixed costs do not depend on these allocation keys and because these costs were once accepted en bloc in order to produce a certain amount of one or multiple product(s). Figure 5 visualizes this critique for a simplified one-product facility. The critique affects cost accounting approaches using actual, normal, optimum, planned and standard costs alike (Riebel, 1994b). Unless the production quantity equals *n* in the figure, the calculation of effective total costs is going to lead to either a shortfall or a surplus cover of fixed costs.

Figure 5: Handling of fixed costs in traditional cost accounting—Riebel's critique (Adapted from Riebel, 1994b, p. 270)



Therefore, Riebel (1994b) states, this approach is not able to depict corporate processes realistically and it hence does not contribute to the overall aim of cost accounting. Eventually, this can mislead cost accountants and other corporate decision-makers to the conclusion that the company profit is both positive from the first production unit on and that it grows proportionally with every additional unit produced (Riebel, 1994b). Furthermore, if the production quantity does not equal the production quantity that was anticipated and calculated, the fixed costs increase wrongfully (Riebel, 1994b). In summary, the chances are high that profits are wrongly calculated due to the proportionalization of fixed costs, leading to incorrect management decisions, especially in the short term. Riebel explains in his article on short-term corporate decisions, which was published in 1967 and reprinted later in his collected edition, that in theory, it is possible to adjust absorption costing data to specific management questions with the help of electronic computing power. However, he immediately weakens this suggestion and argues that the fact that this procedure is possible in theory does not make it advisable in practice: "Why have the costs been allocated to the cost centers and cost carriers in the first place, if they need to be subtracted for control and planning purposes?" [own translation][4] (Riebel, 1994b, p. 283)

Absorption costing had once been developed to enable better pricing decisions and to monitor a company's product range (J. Weber & Weißenberger, 1996). However, it got increasingly hijacked by other management questions and problems, for which absorption costing was not designed, leading to increasingly wrong results in the 50s and 60s (J. Weber & Weißenberger, 1996). The problematic consequences of absorption costing can be structured and summarized as follows (Henrici, 1960, p. 99, cited after Kilger, 1993, p. 51, own translation, original in German):

[4] Own translation, original in German: "Wozu hat man diese Kosten eigentlich zuerst den Kostenstellen und den Kostenträgern zugerechnet, wenn man sie für Kontroll- und Dispositionszwecke dann doch wieder herausrechnen muß?" (Riebel 1994b, p. 283)

1. Sales-related decisions
   a. Elimination of products that generate negative profits, i.e., loss products
   b. Management of sales program
   c. Definition of minimum prices
2. Decisions about production processes in the production sector
   a. Choice between multiple production centers
   b. Choice between in-house production and external procurement
3. Short-time profit planning
   a. Development of profit planning
   b. Monitoring of income in a certain period

According to Plaut (1953) and Kilger (1960), who were contemporaries and research partners, the most common mistake is the elimination of loss products because absorption costing includes fixed costs. More specifically, the proportionate fixed costs will not disappear if management decides to stop production of that respective product. On the contrary, these fixed costs will remain unchanged because they depend on production capacities which cannot be reduced in the short term, while the number of products can be immediately reduced (Kilger, 1960; Plaut, 1953). This critique reached a peak when Sauber (1955) published his commentary titled "Management Appraises Direct Costing—A Play". It vividly illustrates the problem with absorption costing and the activation of fixed costs for overproduction, i.e., the product quantity that is not sold will be stored. One of the protagonists concludes:

> Hold it! Hold everything, Chief! I've got the answer. It's super colossal! We make money when we produce. We don't make money when we sell. So all salesmen I've got running around the country are wasting their time – right? Here's what we'll do. We make the salesmen quit selling. We bring them into the plant, put them on the production line, and produce like mad. And we'll all get rich – right? (Sauber, 1955, p. 461)

This statement may be silly, but it is also true against the background of absorption costing. Consequently, it was high time for a new beginning in cost accounting history.

Interestingly, the roots and beginnings of these ideas can be found in the work of Fredersdorff from 1802, who focused on fixed costs in the ironworks industry (Fredersdorff 1802, cited after Käfer, 1955). About 100 years later, Schmalenbach recognized and clearly stated the problem with fixed costs. He even demanded that fixed costs should not be considered in corporate calculations and pricing (Kilger, 1973b; Schmalenbach, 1899). Albeit the pioneering work of Schmalenbach, it should take many more years until these ideas developed into fruits that are ripe to be harvested in the form of new costing approaches. One reason is that cost accounting was non-existent in most companies and, not to mention *standard costing*, which was still nameless at that time. Rummel, a contemporary of Schmalenbach, also conducted research on cost accounting and dealt with the problem of fixed costs (Rummel, 1967). Rummel claimed that it was illusionary to allocate fixed costs to cost carriers because there was no justification for this. In his view, it is rather a statistical measure without any reasonable or logical argument. Instead of proportionalizing and thus allocating fixed costs to the cost carriers, he argues, they were proportional to calendar time at most. As a result, Rummel also disagreed with absorption costing. Albeit this early and fundamental critique, absorption costing was still a common cost accounting approach in German companies in the 1950s (Kilger, 1993).

Plaut resumed Schmalenbach's and Rummel's research findings and combined them with standard costing in order to develop an innovative, future-oriented approach to cost accounting (Kilger, 1993). The future orientation was a crucial addition to standard costing, and it is the reason why Rummel's and Schmalenbach's ideas were not yet appealing enough to be adopted by industry companies (Kilger, 1993).

2.2.3 Farewell From Absorption Costing: A New Beginning

Over time, more and more companies started to question absorption cost accounting. At the same time, German management theory was influenced by Gutenberg's production-oriented approach (Gutenberg, 1951). Gutenberg's approach was fueled by new production technologies and increased market competitiveness after the end of WWII (J. Weber & Weißenberger, 1996). This led to the development of many new cost accounting systems in the 1950s that strived to be more decision-oriented. Continuously growing companies responded positively to this change of focus, reawakening management accounting ideas and systems that had already been developed and published by the scholars Schmalenbach and Rummel in 1934 (Rummel, 1934; Schmalenbach, 1899, 1934). It was Rummel (1934) who had suggested distributing costs not only in a static and bookkeeping manner anymore. Instead, he suggested adding an analytical component by introducing factors with which the costs can be adapted. His accounting system does not split or allocate overhead costs, but they remain *one block* in a company's short-term income statement. Following this procedure, Rummel named his accounting method *Blockkostenrechnung*, i.e., *block cost accounting*.

From a global perspective, the strongest voices to differentiate the costs were indeed experts in the accounting discipline located in Germany (Pfaff & Troßmann, 2016). With the exception of the one from Riebel, the new approaches focused on the calculation of revenues based on the costs that are dependent from the production volume (J. Weber & Weißenberger, 1996). Despite these significant advancements in the cost accounting field, it took until the mid-80s that full cost accounting was not a main component of commercial education in Germany anymore (R. H. Schmidt, n.d.). Kilger and Plaut were research partners and together, they developed a new and directive cost accounting system, which will be explained in the following (Kilger, 1993; Riebel, 1994b; J. Weber & Weißenberger, 1996). Interestingly, Riebel took a completely different path, although he was driven by the same motivation as the other researchers in the accounting field, i.e., to support decisions and corporate planning (Riebel, 1994b). Kilger and Riebel both agreed to disagree with the different approaches to absorption costing existent at that time. Notwithstanding, they offer different pathways how to deal with fixed and variable costs and how to handle the different cost components as a result. This disagreement and the following academic discourse represent the starting point for the methodological advancement that in turn represents the motivation of this work.

2.2.4 Interim Conclusion

It is notable to recapitulate in retrospect how cost accounting moved from actual costs via normal costs and planned costs to flexible standard costs. This development was motivated by the wish to simplify cost accounting and the curiosity to understand and analyze the data. This led to the adoption of normal cost rates and the breakdown of cost differences into smaller parts such as changes in the capacity utilization rate, which enabled the identification of other deviation factors (Kilger, 1993). The ironworks industry with its fierce competition and the huge size of the companies was a driving force for the developments (A. Müller, 1933; Fredersdorff, 1802, cited after Käfer, 1955). While cost accounting had worked with data from past periods, the time had come to change the perspective of cost accounting from the past to the future in order to gain control over costs. What makes this review interesting and noteworthy from today's perspective is that neither business research nor application in practice is a straight line that is easily comprehensible and transparent. Instead, it is an adventurous journey and a lively academic discourse with many scholars, ideas, currents and trends that additionally were subject to the technological development at that time, politics and world affairs.

Undoubtedly, a lot more could be said about the development and historical background of cost accounting. Having worked through the two main works of Kilger and Riebel, respectively, they shall be highly recommended because they offer a plethora of further information of remarkable scientific quality, detail and elaborateness regarding their cost accounting systems, but also regarding the historical development and the discourse in the research field of accounting until the year of their publication. For example, chapter 2 of Kilger's (1993) monograph contains 366 footnotes in number with additional comments, explanations, references to and recommendations of further literature (Kilger, 1993, pp. 114–132). Both schools of thought found support from prominent representatives such as professors and other experts, representing two camps (Pfaff & Troßmann, 2016). Pfaff and Troßmann (2016) consider the academic dispute a fruitful and necessary basis for the development of a precise and well thought out cost accounting theory.

This body of thought appears to be valuable for the development of the MFCA method. With regard to the sustainability challenge and the responsibility placed on the corporate world, the use of environmental management methods such as MFCA can lead to significant competitive advantages and increase a company's future orientation. Although the method itself is not new, the time has come for MFCA to find wide application in order to promote and increase industrial resource efficiency. Just like the development of cost accounting has been and still is subject to different currents and corporate demands over time, MFCA is also ready for new methodological impulses. The following sections will be guided by the question which of the information is relevant in order to understand the methodological advancement of the MFCA method, leading to MFCA 2.0 and a consulting concept (Chapters 4 and 5). Therefore, it was not the purpose of this chapter to provide a complete overview of cost accounting history, but to build a railing that guides and prepares the reader to enter the conceptual world of MFCA 2.0 and to comprehend the underlying ideas that have fueled the methodological advancement. While the transparent and comprehensible arrangement of the relevant information has been a challenge on its own, it remains a balancing act and not every reader will get the same amount of new information out of the paragraphs. Nonetheless, the rearrangement of ideas can provide food for thought and thus lead to novel ideas and a stimulating read. The following sections will provide their readers with hopefully just that.

2.3 Some Introductory Words on the Topic of Language

Language—being also a research field on its own—can play an important role in other research fields. At the time of writing these lines, there is a great multitude of options how to overcome language barriers such as Google Translate[5], DeepL[6] and ChatGPT[7], to name but three. Although it may be difficult to imagine for members of the generation of digital natives, there was a time when language could represent an actual barrier, not only in academia. Therefore, as pointed out in Section 1.4, this thesis pursues to build a bridge over the river of language barriers, which

[5] https://translate.google.com/
[6] https://www.deepl.com/translator
[7] https://chatgpt.com/

reduced international perception, awareness and discussion of the topic in the past. As J. Weber and Weißenberger (1996) pointed out, "[t]his discussion has never found much reflection in cross-national literature, which may have been caused by language barriers" (p. 2). For this reason, Chapter 2 is equipped with many direct quotes so that the original ideas do not get distorted. These text passages will not be treated as paraphrases, which the American Psychological Association (APA) Style 7th edition would recommend (APA, 2020). Instead, this work strives for a clear and unbiased literal translation of the original text in order to make these ideas available to an English-speaking audience, rather than paraphrasing them.

While *Kilger's Grenzplankostenrechnung* can be translated as "Kilger's Flexible Standard Costing" (J. Weber & Weißenberger, 1996, p. 2), Riebel himself did not translate the title of his work for publications in English (Riebel, 1994a). Riebel's designation is more difficult to translate because he himself chose the German version "Relative Einzelkosten- und Deckungsbeitragsrechnung" when he published his work in English (Riebel, 1994a). Since one goal of this thesis is to deal with these accounting systems in a reflective and critical way, Weber's and Weißenberger's suggestion "Riebel's Generic Direct Costing" will be taken as a basis. Both authors included the component "Deckungsbeitragsrechnung" in the title of their main work, respectively, which means "contribution margin accounting" in English, the following hopefully unequivocal translations will be used hereafter, respectively.

- German: *Flexible Plankostenrechnung und Deckungsbeitragsrechnung* (Kilger, 1993)
  English: "Kilger's Flexible Standard Costing and Contribution Margin Accounting" [own translation] (Kilger, 1993)
- German: *Einzelkosten- und Deckungsbeitragsrechnung* (Riebel, 1994b)
  English: "Riebel's Generic Direct Costing and Contribution Margin Accounting" [own translation] (Riebel, 1994b)

In line with the APA Style 7th edition (2020), this work puts the German title of their work in quotations marks, respectively, if the book is addressed. If the cost accounting system and related ideas or concepts are addressed, the designation is written in italics, respectively, in order to accentuate their central role in this dissertation.

2.4 Kilger's Flexible Standard Costing and Contribution Margin Accounting

Wolfgang Kilger (1927–1986) was a German professor for business administration at Saarland University in Germany and a student of Erich Gutenberg (Kilger et al., 2012). He published his main work "Flexible Plankostenrechnung und Deckungsbeitragsrechnung" in 1961 in its first edition, which was based on his habilitation thesis. Kilger's ally Plaut developed the ideas first and pioneered the approach, but Kilger developed the academic version, documented and published the new approach. His work led to a cost accounting classic that was revised multiple times and published in its 13th edition in 2012 (Kilger et al., 2012).

2.4.1 Plaut's Motivation for a New Cost Accounting Approach

Hans-Georg Plaut was the first person in Germany to present *Flexible Standard Costing and Contribution Margin Accounting* as a closed accounting system in Germany (Kilger, 1993). A closed accounting system takes all cost types into account, and it aligns the data regularly with the financial accounting department and the income statement (Schweitzer & Küpper, 1991). During WWII, Plaut worked in an armament factory in the metal processing industry, where *standard costing* was used. Already in 1946, Plaut had become self-employed as business consultant and he founded the consulting company Plaut (msg Plaut AG, 2025; J. Weber, 2006). Around 1950, he started working on an alternative to absorption costing due to the incorrect decision support it provided for profit analysis and planning, which he then named "Grenzplankostenrechnung" (Kilger, 1993). In the beginning, Plaut focused on a marginal approach including proportional costs only. He added fixed costs in the form of additional calculations at a later time (Kilger, 1993).

In accordance with Plaut's innovative approach, the consulting company *Plaut* implemented the marginal approach called flexible standard costing in industry practice (Kilger, 1993). In 1974, the company *Plaut Software GmbH* was founded in Germany, specializing in accounting software (J. Weber, 2006). Without questioning Plaut's achievement, it was Kilger who then lifted Plaut's work on an academic level (Kilger, 1993; Riebel, 1994b; J. Weber & Weißenberger, 1996).

2.4.2 The Beginnings of Kilger's Flexible Standard Costing and Contribution Margin Accounting

Kilger's Flexible Standard Costing and Contribution Margin Accounting is a form of flexible standard costing with a strict differentiation between fixed and proportional costs, being a result of the criticism of *absorption costing* (cf. Subsection 2.2.2). At this point, the readers shall be reminded (cf. Subsection 2.2.3) that the ideas that Plaut and Kilger described were also developed in *direct costing* in the US (K. Weber, 1960b) and *marginal costing* in the UK (Lawrence & Humpreys, 1947). However, Plaut developed his approach between 1950 and 1952 without any external influences and published the term *Grenzplankostenrechnung* for the first time in 1952, which is equivalent to *marginal standard costing* in English (Plaut, 1952). It was Käfer who discovered the parallel developments and pointed them out (Kilger, 1993). The designation "marginal" indicates that infinitesimal changes in the production volume are analyzed, leading to differential costs. This relation is only correct if the costs in all cost centers increase linearly because otherwise, marginal costs and average costs will diverge. Kilger acknowledges this theoretical limitation, but he responds with the argument that this condition can be seen as a given in cost accounting practice (Kilger, 1993).

The name of this cost accounting approach and the basis of its concept date back to Schmalenbach's work from 1899 and the following years, in which he had already recognized the problem of the proportionalization of fixed costs (Kilger, 1973b; Schmalenbach, 1899). In search of an appropriate name for his newly developed cost accounting system, Schmalenbach suggested the names *proportional cost accounting* (*Proportionalkostenrechnung*) and *marginal cost accounting* (*Grenzkostenrechnung*), but he then found them to be too limited in their meaning, so that he suggested the name *operating value accounting* (*Betriebswertrechnung*) (Kilger, 1973b). Moreover, Kilger explains that the name *contribution margin accounting* became popular because it is an effective tool to plan and control period results. However, he opposes, the name *marginal costing* would be more appropriate because it covers multiple branches of cost accounting. Additionally, marginal costing can also be used to minimize production costs on the shop floor (Kilger, 1993). Interestingly, Kilger explains in the preface to the eighth edition, flexible standard costing and contribution margin accounting and marginal costing successively converged over time. In order to be more practice- and decision-oriented, flexible standard costing and contribution margin accounting developed towards marginal costing. Marginal costing, in turn, was supplemented with a full-cost analysis. Therefore, Kilger and his colleagues decided to retain the generic designation *flexible standard costing* (Kilger et al., 2012).

This dissertation is based on Kilger's main work titled "Flexible Plankostenrechnung und Deckungsbeitragsrechnung" (Kilger, 1993). In the preface of the eighth edition, Kilger explains that he has now included a detailed presentation and discussion of the different direct costing methods existent at the time of writing including Riebel's (1994b) approach, which is also of great importance for the present dissertation. Kilger's work was reissued in 1993 in its 10th edition by Kurt Vikas, an Austrian professor and scholar for internal corporate accounting and cost management, who knew Kilger personally (Kilger et al., 2012). For this work, the 10th edition was chosen. It was also edited by Kurt Vikas, and it contains a comprehensive case study including software support (Kilger et al., 2012). The 11th edition was characterized by Pampel, who added new ideas, developments and viewpoints to the work, and by Vikas, who took care of the form of presentation thereof (Kilger et al., 2012, preface to the 13th edition). The currently newest 13th edition was also edited by Pampel and Vikas and released in 2012.

2.4.3 The Main Purpose of Kilger's Flexible Standard Costing and Contribution Margin Accounting

Kilger's Flexible Standard Costing and Contribution Margin Accounting aims to provide more accurate results by separating proportional from fixed costs. Using Kilger's wording, this active differentiation with its consequences felt like a "'revolutionary' step forward" [own translation][8] (Kilger, 1993, p. 11) for the cost accounting community. This revolutionary change at that time opened new perspectives for the application and purpose of cost accounting because the differentiation between fixed and proportional costs generates new information and arguments for corporate decision-making. For example, short-term minimum prices could now be calculated (Kilger, 1993). In addition to these lower price limits, the contribution margins need to be kept in mind, which should not be hastily misinterpreted as profits, but merely as contribution to the coverage of the fixed costs. As soon as the total amount of contributions exceeds the total of fixed costs over the planning horizon, the break-even point is reached, from which onwards the company makes profit (Kilger, 1993). Consequently, the contribution margin plays an important role in two respects. First, the product range that a company offers can be extended with products as long they have a positive contribution margin and until the production capacity is reached (Kilger, 1993). Second, the contribution margin serves as a decision criterion in the situation of a production-capacity based bottleneck (Kilger, 1993). In such a situation, the different contribution margins can provide guidance when optimizing the use of production capacities in order to successively cover fixed costs (Kilger, 1993).

For this purpose, the contribution margins per unit are divided by the quantity of the bottleneck per unit, leading to *relative contribution margins*, which are descriptively named *contribution per unit of limiting factor* or *marginal income per the scarce factor* in Anglo-American research literature (e.g., Jaedicke, 1961). In the following step, these relative contribution margins can be used to rank the different products. Following that ranking, additional products can be produced until maximum capacity is reached (Kilger, 1993). The *marginal product* is the one just before full capacity is reached. The products ranked below the marginal product will not be produced in the planning horizon anymore. This procedure can also be used in case of multiple bottlenecks as well as in the case in which new potential products or product orders are considered

[8] Own translation, original in German: "[a]ls „revolutionärer“ Entwicklungsschritt" (Kilger, 1991, p. 11)

or stand in competition to the existing production plan or each other. Using the method of linear programming, such complex decision-making problems including more than one bottleneck can be solved and the company's profit optimized (Kilger, 1973a). Interestingly, the fast development of data processing in the following years took the wind out of the critics' sails.

Moreover, *Kilger's Flexible Standard Costing and Contribution Margin Accounting* also offers guidance in times when produced and sold quantities diverge, i.e., stock increase or reduction took place, from a different angle compared to absorption costing. While both methods treat proportional costs in the same way, they disagree about fixed costs. Absorption costing activates fixed costs in the time period the product is sold, whereas *Kilger's Flexible Standard Costing and Contribution Margin Accounting* activates fixed costs in the time period the product is manufactured. This is in accordance with the perception that fixed costs accrue regardless of production and independently of the production volume. As a result, profit is smaller compared to absorption costing in times of overproduction (Kilger, 1993). This is the difference Sauber (1955) addressed in his comic and absurd commentary with the statement "We make money when we produce" (p. 461) (cf. Subsection 2.2.2).

While Kilger's first edition of his book completely rejects absorption costing, later editions recommend parallel calculations for specific purposes. Moreover, Kilger and Riebel both make critical notes about their cost accounting approach in later editions of their work. In the original cost accounting system, planned cost and wage rates are assumed to be fixed over a year, which is not realistic and thus bears improvement potential. Therefore, Kilger developed a dynamic version of his approach (cf. subsection 1.344.4 "Die dynamische Grenzplankostenrechnung" in Kilger's [1993] work). It allows changes of cost and wage rates, specifications for decision-specific adjustments, and it includes maturity aspects for the time horizon under consideration (Kilger, 1993; Kilger et al., 2012). However, this advancement did not become popular in practice because according to Kilger, it focuses too much on the payment due date. Kilger et al. (2012) then argue that the relationship between the increase or decrease of resource consumption in combination with the capacity utilization should be the center of the *dynamic* approach, which can only be solved by corporate cost managers and not by cost accountants (Kilger, 1993). Albeit these expansions, the concept of marginal costs remained the core of *Kilger's Flexible Standard Costing and Contribution Margin Accounting*. Its goal was to provide decision support for a specific capacity level and to calculate profits based on defined sales numbers (Franz, 2017b).

2.4.4 Conclusion of Kilger's Approach

Kilger's and Plaut's work is of central importance for the progress and improvement of cost accounting, which is why Kilger's book has been updated and reissued in its 13th edition in German (Kilger et al., 2012). The Plaut consortium was founded in 1946 and has existed and developed since then (cf. Subsection 2.4.1) (msg Plaut AG, 2025). Furthermore, *Kilger's Flexible Standard Costing and Contribution Margin Accounting* is still part of Horsch's (2023) textbook on cost accounting. Moreover, Horsch points out how important Schmalenbach's work was for the development of cost accounting in Germany. Interestingly, Kilger himself emphasizes Schmalenbach's groundbreaking work, in which he pursued the ultimate goal to provide corporate decision support with a new form of cost accounting (Kilger, 1993).

Therefore, the beginnings of direct costing were earlier than in the US, although they appeared later in the form of a closed cost accounting system in Germany (Kilger, 1993). This is an important finding in hindsight: Although or because Schmalenbach was undoubtedly a pioneer of his time, he was ahead of the times because the time was not yet ripe for his innovative ideas.

Schmalenbach's target group was not in need of the advantages of his decision-orientated approach. Nevertheless, Schmalenbach unswervingly refined and published his thesis that fixed costs are a problem in cost accounting, and indeed, this became a decisive cornerstone for the further development of cost accounting many decades later (Kilger, 1993). Schmalenbach's unconventional and opinionated character trait was of vital importance and qualified him as founder of contribution margin accounting (Kilger, 1993).

Coming back to Kilger, the value of the framework conditions that surrounded his cost accounting approach should not be underrated. He carefully chose the terms and definitions of his approach in consideration of the level of development at that time. Moreover, the institution AGPLAN played a central role regarding the dissemination and marketing of the new approach (cf. Subsection 2.2.1). It certifies the practice-orientation, conviction and strong will of the persons involved and it offered a seminar about standard costing and its new forms including flexible standard costing. In 1983, the Plaut Group undertook the seminar (Kilger, 1993). As a result, *Kilger's Flexible Standard Costing and Contribution Margin Accounting* increasingly gained recognition over time and became part of operational planning. However, in order to provide accurate decision support, cost planning needs to be integrated and connected with all other corporate planning activities, Kilger (1993) remarked. In other words, if flexible standard costing is used without consideration for other planning activities, it cannot provide effective decision support, thereby questioning the effort involved. This aspect will be taken up again when it comes to the implementation of MFCA in a company.

2.4.5 Critical Assessment of Kilger's Flexible Standard Costing and Contribution Margin Accounting

Coming to challenges and critical arguments about *Kilger's Flexible Standard Costing and Contribution Margin Accounting*, it should be noted that the maturity structure of the costs highly depends on the planning horizon of the cost accounting considerations. The question of whether a cost component is fixed or flexible can only be answered with regard to a predefined time horizon. The results are highly specific and are therefore not transferable to another question. Consequently, every planning horizon requires the review of the maturity structure of the costs, which is associated with additional effort.

Moreover, Kilger's approach is more complex than absorption costing and the concept of direct costs bears the danger of misinterpreting it as a general lower price limit (Kilger, 1993). However, this lower price limit is only correct within the time horizon under analysis. Furthermore, it is a price limit for internal decisions, and it must not be confused with selling prices. The reason for the limited validity is that the costs which are considered fixed within the time horizon under analysis still need to be covered with contribution margins. This knowledge is indispensable when using the cost accounting approach and it requires instructions, training and time to make correct decisions.

According to Pfaff and Troßmann (2016), Kilger can be criticized for showing too much willingness to compromise, for example, regarding lax definitions and regarding the implementation of his approach. As a result, it leads to unclear statements that weaken his approach (Pfaff & Troßmann, 2016). Riebel also criticizes *Kilger's Flexible Standard Costing and Contribution Margin Accounting* and US-American direct costing for theoretically too indefinite and coarse (Riebel, 1979). He argues that if product quantities change, there are multiple ways for a company to adapt. Moreover, this change can impact the costs in many ways such as the production method or the mode of dispatch (Riebel, 1979). Kilger counters this argument with the information that product quantities are not an appropriate indicator for a company's capacity utilization, but reference values that stand in relationship to the costs (Kilger, 1993). Kilger (1993) adds that although all costs can be analyzed in relationship to these reference values, the number of reference values needs to be limited for practical reasons. Nevertheless, Kilger (1993) concludes, Riebel's (1979) point of criticism was not applicable to the way his cost accounting approach was designed and used in corporate practice.

2.4.6 The Development From Standard Costing to Direct Costing in the US

Taking a look at the development of cost accounting in the US, K. Weber (1960a) concludes in his literature review of American cost accounting that Emerson, who published several articles on standard costing in the Engineering Magazine (e.g., Emerson, 1908) is the "father of American standard costing" (K. Weber, 1960a, p. 7). Harrison, who was also Emerson's research colleague and who focused on the practical implementation of the approach, also contributed significantly to the development of standard costing (K. Weber, 1960a). Harrison was not only a pioneer for standard costing in the US—he also paved the way for *direct costing*.

Direct costing appeared as *closed* cost accounting system in the US for the first time (Kilger, 1993). A closed accounting system is one that incorporates all cost types, regardless of whether the cost center managers have an impact on the height of the costs through their decisions or behavior, respectively (Kilger, 1993). Additionally, in a closed cost accounting system, costs are regularly aligned with the financial accounting department and the income statement (Schweitzer & Küpper, 1991). The pioneering work for *direct costing* was done by the two Americans Harrison and Harris based on industry practice, but independently from each other. Harrison developed the direct costing approach within an industry project in 1935 and published it two years later (cf. Wright, 1962). Almost at the same point in time, but independently from Harrison, scholar Harris moved from standard costing to direct costing as well because he had realized that absorption costing, i.e., full costing, had not been able to deliver the information he needed for the specific question regarding his company (Beckett, 1955). In 1936, Harris published his famous article titled "What Did We Earn Last Month?", which also coined the designation *direct costing*.

Despite these research and practice activities, direct costing did not become successful and did not automatically find recognition and implementation (Kilger, 1993). After the end of WWII, companies opened up for new cost accounting approaches and corporate interest in direct costing increased. To help the young approach of direct costing to take root both in academia and in the economic world, the *National Association of Cost Accountants* (N.A.C.A., founded in 1919 and renamed as *National Association of Accountants*, NAA, in 1957) promoted it in different forms such as systematic descriptions, publications and research reports. Moreover, the association put the new approach up for discussion and further advancement in the form of research committees and discussion groups (Kilger, 1993). As a result, according to an empirical study conducted by the NAA (1961), direct costing was adopted widely in the American industry from 1953 onwards. The respondent companies stated that they adopted direct costing as a response to the insufficient decision support provided by all forms of absorption costing. Direct costing, on the contrary, is able to improve profit planning and corporate performance analyses (NAA, 1961). Despite the positive development, direct costing faced practical challenges because it does not provide correct values for commercial and tax balance sheets. Especially in the US, financial accounting and operational accounting are usually not separate, which requires additional effort when practicing direct costing (Kilger, 1993).

Although *direct costing* is the US-American equivalent to *Kilger's Flexible Standard Costing and Contribution Margin Accounting*, Kilger (1993) criticizes this designation as misleading because it suggests that only the direct costs are included in the calculations. However, American *direct costing* includes not only direct costs, but all cost types appearing in the cost centers that are proportional. It is therefore in accordance with Kilger's approach. If only direct costs are included, it is called *prime costing* (K. Weber, 1960b).

2.5 Riebel's Generic Direct Costing and Contribution Margin Accounting

Paul Riebel (1918–2001) was a German professor at Goethe University Frankfurt am Main, Germany (R. H. Schmidt, n.d.). He initially studied chemistry and economics, and he also wrote a habilitation thesis. His academic work represents the development and elaboration of the cost accounting system titled *Generic Direct Costing and Contribution Margin Accounting—Fundamental Questions of a Market- and Decision-Oriented Corporate Accounting Approach* [own translation][9]. It was published in the form of a compilation, i.e., as a collection of his individual publications in 1972 in its first edition. The present dissertation is based on the seventh edition of this book, which has been revised and substantially expanded by Riebel himself (Riebel, 1994b).

2.5.1 Introduction of Riebel's Generic Direct Costing and Contribution Margin Accounting

The systemic problems of absorption costing motivated Riebel to design a new cost accounting system without contaminations from the past. His goal was to design a system that takes a company's individual processes and circumstances into account and that can be used within the free market economy (Riebel, 1994b). The roots of his line of argumentation can be found in his education as chemist and the focus of his diploma thesis on joint production processes, i.e., chemical processes with more than one output flow or product. He concluded that in multi-product processes, costs cannot be allocated via quantity shares (Riebel, 1950). Albeit some technical function may be useful for preliminary calculations, they are not useful for the allocation of costs (Riebel, 1994b). Therefore, Riebel developed his method around the *identity principle*, as will be further explained in the following. Instead of trying to identify direct costs and allocating overhead costs to product units, he suggests identifying the costs that can be led back to a particular decision. Consequently, Riebel only accepts the costs in a calculation that stand in direct relation to a particular decision object. His credo and final goal were to compute exact information on cost, revenue and operating results for a company (Franz, 2017a).

In May 1959, Riebel published his cost accounting concept in the form of an article titled "Calculating With Direct Costs and Contribution Margins" [own translation][10] (Riebel, 1959) for the first time. It was followed by strong reactions in both directions, which surprised him as a researcher (Riebel, 1994b). Three years before that, he had published an article addressing the question of how cost accounting can contribute to the purpose of corporate operating control and disposition (Riebel, 1956), which—on the contrary—received little attention (Riebel, 1994b). The considerable attention Riebel received for his publication in 1959 revealed that the distance between

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[9] Own translation, original in German: "Einzelkosten- und Deckungsbeitragsrechnung – Grundfragen einer markt- und entscheidungsorientierten Unternehmensrechnung" (Riebel, 1972)

[10] Own translation, original in German: "Das Rechnen mit Einzelkosten und Deckungsbeiträgen" (Riebel, 1959)

his approach and the other approaches is larger than that between the approaches of full-cost accounting on the one hand and direct costing on the other (Riebel, 1994b).

2.5.2 The Setup of Riebel's Generic Direct Costing and Contribution Margin Accounting

The core concept of *Riebel's Generic Direct Costing and Contribution Margin Accounting* is to trace costs back to their beginnings in order to decide whether a cost component is imputable to the reference object under analysis or not (Riebel, 1994b). As a result of this statement, the logical and consequential question is what the reference object actually is. A reference object can be any aspect of corporate interest (Riebel, 1994b). In Riebel's accounting system, the different reference objects are organized in hierarchical order, leading to a stepwise coverage of overhead costs (Riebel, 1994b). Riebel followed Schmalenbach's recommendation to set up a purpose-neutral accounting database that can be used as a basis for many special analyses (Riebel, 1994a). Moreover, he did not allow any allocation or break-down of fixed costs whatsoever. Once this basic accounting system has been built, special analyses can be derived from it in the next step (Riebel, 1994a). The starting point for these calculations is a situation that offers multiple decision options in the form of measures, actions and activities, representing the core objects of analysis.

This procedure and logic differentiate Riebel's cost accounting system from all other systems at that time. Using Riebel's own wording, "[t]he special aim was the development of a true reconstruction of reality in accounting—as good as possible—which bears intersubjective examination ex post" (Riebel, 1994a, p. 515). Therefore, this accounting system only allows the following data (Riebel, 1994a, p. 517):

- Physical quantities of real goods including services
- Outgoing and incoming payments or physical quantities or cash
- Expenditures and receipts and other claims and obligations on later payments

Furthermore, the cost system allows cost components to be imputed to revenues that are both caused by the same decision. This feature shall make Riebel's approach practice- and action-oriented (Riebel, 1994b). In order to fulfil this claim, his accounting system is grounded on the identity principle, which also leads to a decision-oriented view on costs.

2.5.3 The Journey Towards the Identity Principle: The Causation Principle

There are multiple ways to distribute costs to corporate performances, called *distribution principles*. The causation principle is one such principle and it can be interpreted and applied in different ways. Riebel studied the work of the German philosopher Hartmann (1951) on teleological thinking, who bases his line of thought on the four kinds of causes that existed in medieval philosophy (Riebel, 1994a, 1994b). Hartmann (1951) translates them as follows (Hartmann, 1951, p. 47, own translation from German):

- Causa materialis—matter
- Causa formalis—substantial form, shape or essence
- Causa finalis—purpose or aim
- Causa efficiens—movement

In the following two paragraphs, causa efficiens and causa finalis will be explained in detail regarding Riebel's identity principle.

2.5.3.1 The Causation Principle as Causa Efficiens

The advancement in the field of natural science led to a focus of the use of the term *cause* in the sense of *effecting cause*, which is not the exact meaning of *causa efficiens*. In 1969, Riebel published an article titled "The Questionability of the Causation Principle in Accounting" [own translation][11]. It is also part of his compilation, in which he presents and examines this principle (Riebel, 1994b). With a focus on overhead costs, the article analyzes the relationship between two quantities that show a positive linear correlation (Riebel, 1994b). It is important to not confuse correlation with proportionality. Not every correlation automatically means that the relationship is also proportional. Regarding causation, the following options are possible (Flaskämpfer, 1949, own translation from German):

- A caused B
- B caused A
- A and B are both cause and effect likewise
- A and B are both the result of a third variable C

Otherwise, there is no causal relationship at all, i.e., a correlation does not make sense (Flaskämpfer, 1949). Riebel's (1994b) following train of thought transfers these ideas to the existence of overhead costs. He concludes that overhead costs related to operational readiness cannot be subsumed in the above-named options because overhead costs also accrue if no product units are produced at all. Therefore, no causal relationship can be detected (Riebel, 1994b). In the special case of direct costs, which are related to the quantity consumed in the production process, these are not automatically proportional because oftentimes, the costs are subject to special conditions such as quantity discounts, bulk prices or other individual conditions such as shipping costs (Riebel, 1994b). At this point, Riebel references other scholars whose research focused on costs and their characteristics, such as H. J. Müller (1950) and Gutenberg (1951). Their key point is that in the special case when a process directly causes the consumption of goods, no statement can be made about the costs of the goods at all. However, if that special case is true that a process directly causes the consumption of goods, the corresponding costs do not necessarily follow the physical consumption curve since the cost curve usually depends on many other factors (Gutenberg, 1951; H. J. Müller, 1950).

Nine years after the article mentioned at the beginning of this paragraph, Riebel published another article on this topic. He concludes that the argument that the consumption of goods leads to a specific amount of product output was not an appropriate starting point for the calculation of the incurred costs at all (Riebel, 1978). He argues that there is a plethora of circumstances leading to non-linear remunerations such as commissions, taxes or other fees. The article comprises illustrations of six different non-linear remuneration functions (Riebel, 1978, p. 416f.). In summary, no relationship in the sense of causa efficiens between purchased goods and produced goods can be detected. Based on this, those costs related from the purchased goods cannot be allocated to the produced goods (Riebel, 1994b).

[11] Own translation, original in German: "Die Fragwürdigkeit des Verursachungsprinzips im Rechnungswesen" (Riebel, 1994b)

2.5.3.2 The Causation Principle as Causa Finalis

Hartmann designed a three-step process that includes causal and final aspects, demonstrating that every final process requires and includes a tangible causal process, although he does not provide a definition of the term *causality* (Hartmann, 1951, p. 69). The three steps are the following (Riebel, 1994a, p. 520):

1. Determination of the goal
2. Choice of means which are appropriate to reach the goal
3. Realizing the decisions by using an appropriate causal process

This three-step process can also be interpreted with regard to cost accounting theory. According to this train of thought, the consumption of goods in production processes is a side effect that was not the original goal, but it comes into existence for the desired effect or goal. To illustrate his point, Riebel (1994b) takes up the ideas of Kosiol (1979) who defines the concept of cost causation with regard to causa finalis, stating that goods are only consumed in a teleological sense if they are physically transported and thus the costs are caused by tangible pipelines.

Instancing the relationship of procurement, supply and the consumption of goods, these three do comprise an immediate relationship between means and end because the costs that come into existence with these activities are directly related to the costing objects. However, in the case of manufacturing processes, costs cannot be attributed with the help of causa finalis or the final principle since they have been purchased and even passed the factory gates already (Riebel, 1994b). These are the reasons why Riebel developed the identity principle.

2.5.4 The Evolution and Meaning of the Identity Principle

The identity principle represents the core of Riebel's cost accounting system. It can be understood as antithesis to all the other cost accounting systems existent at that time, and it has generated diverse reactions. Its evolution, meaning and consequences will be portrayed in the following paragraphs.

2.5.4.1 Preceding Ideas Leading to the Identity Principle

Riebel's line of argumentation that eventually led to the identity principle started with the topic of order size. Schmalenbach had paved the ground with the finding that costs are highly dependent from a company's capacity utilization (Schmalenbach, 1908). Schäfer, who was Riebel's teacher, carried this topic forward and refined it by developing ideas to make the relationship between costs and order size more tangible (Schäfer, 1931). The title of Riebel's article that contained the early ideas for the identity principle is "The Problem of the Minimal Order Size" [own translation][12]. It clearly points out the difficulty to define the size of an order that generates exactly the revenue amounting to the costs resulting from its fulfilment (Riebel, 1994b). The formulation of this idea lead to the critique that the term "minimal order size" does not represent the smallest order size a company should generally accept since a small order size can be the beginning of a profitable business relationship in the future (Riebel, 1994b).

[12] Own translation, original in German: "Das Problem der minimalen Auftragsgröße" (Riebel, 1994b)

Leaving this critique aside for a moment, the search for the aforementioned order size poses the question what costs can be assigned and allocated to an order. Riebel developed the thesis that only costs should be included that clearly and unambiguously show a causal link between the order under investigation on the one hand and the cost on the other hand (Riebel, 1994b). In order to decide whether a certain cost component is related to the object under investigation, the question needs to be examined whether that cost component would reduce to zero if the object did not exist and whether that cost component would increase with every additional unit produced (Riebel, 1994b). This applies only to the cost behavior of variable costs that are directly dependent from the production quantity, Riebel (1994b) concludes, because stand-by costs do not show this causal relationship.

Notwithstanding this finding, the article allows and foresees the proportionalization of fixed costs for certain purposes (Riebel, 1994b). Since no causal relationship exists, those values must always be used with caution and imperatively be interpreted against the background of that specific purpose, which may be planning and monitoring purposes. Moreover, these calculations can be helpful for pricing as they, for example, deliver average overhead costs, i.e., the overhead costs that the product range included in the calculations should cover on average (Riebel, 1994b). To emphasize his point, Riebel (1994b) instances the per capita indicator of iron production, which is an indicator that shows no causal link at all. This is a clear description of how to handle and cautiously interpret cost accounting figures without losing sight of the purpose or even misinterpreting the figures, posing the risk of making wrong corporate decisions.

2.5.4.2 The Identity Principle

Riebel developed the identity principle as cornerstone of his cost accounting system. It goes both beyond *causa efficiens* and also beyond *causa finalis*. According to Riebel (1994b), neither of them is able to generate unambiguous results because they both leave room for subjective influences. Therefore, Riebel offers a third interpretation of the causation principle, leading to the true causation of the costs. He defines it as follows:

> Hence I define identifiable costs ('Einzelkosten') as incremental expenditures (payments and liabilities) or outlays resulting from a decision about the object under consideration. Contributions to profit (and common costs etc.) arise only if the matched revenues (receipts) and costs (expenditures) have their origin in the same (identical) initial decision. (Riebel, 1994a, p. 522)

In cost accounting jargon, the identity principle means that cost allocation to cost objects is only correct if the cost object and the costs are both a result of the same decision (Riebel, 1994a). This principle is a strict concept that does not require the separation of fixed and proportional costs, but instead, it views the costs in light of the cost object and time period, which are both defined at the beginning of the analysis. A cost object may be a physical unit, a cost center, a corporate segment or an event (Riebel, 1994a). In this logic, a cost component is either *specific* or *common* (Riebel, 1994a). If a cost component cannot be traced back to the same decision as the cost object, it is characterized as common with regard to the cost object under analysis. However, it may be characterized as specific with regard to a cost object that belongs to a higher hierarchical level. As a result, whether a cost component is specific or common, is not a universal question, but it depends on the cost object being examined. Since there is a large number of decisions and cost objects within a company, increased attention needs to be paid when applying the identity principle to make sure that costs and cost object are clearly the result of the same decision (Riebel, 1994b). According to Riebel, the identity principle is of universal character and decision orientation. Moreover, he clearly states that this does not mean that all accruing costs in a company are necessarily to be allocated to cost objects (Riebel, 1994b). This is an important note, as most cost accountants were used to absorption costing at the time Riebel developed and presented his new approach to the public.

It may seem tempting to rate Riebel's line of argumentation as too theoretical and thus an unnecessary specification of academia (Riebel, 1994b). Compared to the two aforementioned interpretations of the causation principle causa efficiens and causa finalis, a possible motivation may lie in the fact that the interpretation as causa efficiens is more common in the natural sciences and thus may be easier to comprehend. The identity principle is not a specification of the causa efficiens because it does not look for the reasons of the events, but it rather reveals commonalities in the origin of the events (Riebel, 1994b). As a result, the identity principle does not contradict the principle of causation, but it rather offers a third interpretation that goes beyond causa efficiens and causa finalis because it considers corporate decisions as the root cause of production activities, which in turn bring forth costs and cost objects (Hohenbild, 1974). Riebel (1994b) gives two examples to illustrate his point: contractual agreements that include certain payments and services stand in direct relation to the occurrence of costs. Therefore, the decision to sign the contractual agreement represents the cause, and the payments and services are consequences (Riebel, 1994b). The second example Riebel (1994b) gives comprises a worn-out corporate vehicle that requires maintenance and repair works in order to be available in the future. In this situation, he argues, the costs that accrue due to the maintenance and repair works are not caused by the wear and tear during the vehicle's use, but they accrue because of the decision to bring it into a serviceable condition again, i.e., the decision to repair it. This decision, in turn, is motivated by the decision or wish to use the vehicle in the future (Riebel, 1994b).

Riebel presents a decision-based definition of the term *cost*, which is radically different from the value-oriented understanding of the term. The value-oriented understanding starts with the physical quantities and multiplies them with transfer prices to determine the costs (Hummel, 1970, 1983). It provided the basis for all accounting systems common at that time (Hummel, 1970, 1983). Riebel (1994b) criticizes this approach because its purpose and goal cannot be stated intersubjectively. On the contrary, his decision-based approach to the concept of costs implies a certain measure that follows the decision (Riebel, 1994b). That measure ultimately triggers expenses and payments at the end of the day that would not exist without the decision for that measure. Hence, this kind of costs only occurs in combination with an object, which in this context represents a decision-alternative with a corresponding measure. Any payment that lies in the past and that cannot be refunded or whose corresponding decision cannot be undone, must not be considered for future decisions (Riebel, 1994b). These rules align cost accounting with investment calculations, which used to generate differing results as they included different cost components, respectively (Riebel, 1994b).

In summary, the identity principle presents a new definition of the term *cost*, and it looks at it from the viewpoint of a decision (Riebel, 1978, 1994b). With the identity principle, Riebel builds on the works of Coole (1936), Vatter (1945) and Hummel (1970) who had delved into the concept of costs and who had contributed significantly to this research field, respectively. Once again, it becomes apparent how important it is to review existing knowledge and research literature as inspiration for innovative ideas and methodological improvement. Riebel's approach to cost accounting using the identity principle was not only unusual at the time of its development, but it represents an unusual body of thought until this day. However, this does not diminish its value.

2.5.4.3 Implementation of the Identity Principle in Practice: Joint Production and Complexity

The identity principle has far-reaching implications for the practice of cost accounting since it does not allow the allocation of costs that do not result from the exact same decision. Therefore, if a decision has been made to produce multiple products, e.g., a product bundle, which is oftentimes the case in daily business, this product bundle will also represent the cost object in the following calculations (Riebel, 1994b). In these cases, the wish to divide and allocate the process inputs is oftentimes large, leading to arbitrary and therefore wrong results (Riebel, 1994b). Being trained as a chemist, Riebel was highly familiar with chemical reactions and the stoichiometry behind them. Following his identity principle, he rejects the allocation of input materials or energy inputs that are required for a specific chemical reaction by all means. Consequently, all products emerging from the same production process, i.e., multi-product processes, can only be analyzed together in *Riebel's Generic Direct Costing and Contribution Margin Accounting* (Riebel, 1994b). Pfaff and Troßmann (2016) find that the discipline of cost accounting has not succeeded in integrating joint production processes at least until 2016, in which their overview was published. Notwithstanding their finding, they demand a cost accounting approach for the future that is able to handle joint production processes and refer to Riebel who had defined product bundles as actual decision variable. This could enable a quantum leap with regard to undesired side effects of production processes such as production waste, which are often not in accordance with sustainability criteria (Pfaff & Troßmann, 2016). *Kilger's Flexible Standard Costing and Contribution Margin Accounting* treats multi-product processes in a similar way because variable production costs of co-products must not be distributed either. Instead, they are overhead costs and thus form their own contribution margin. The other costs, on the contrary, should be allocated using appropriate allocation keys according to Kilger's approach (Kilger, 1993). In summary, Riebel and Kilger agree that the costs of co-products, i.e., the result of multi-product processes, must not be divided between the products. Nevertheless, their cost accounting systems suggest different pathways, respectively. While Riebel focuses on the product bundle as cost object, Kilger strives to identify the contribution margin that is caused by the co-products together.

Furthermore, when applying the identity principle in practice, it may appear helpful to reduce the degree of complexity by limiting the chain of actions and by decreasing the importance of certain circumstances and side effects in order to accelerate the calculations. Riebel (1994b) argues that, for example, discount deductions and interest costs can indeed be neglected because they are first subject to decisions that can be made at a later point in time. Second, they are oftentimes independent from corporate disposition activities. In this case, payout values should be included in the calculations instead of expense values (Riebel, 1994b). Another aspect relating to practicality is the introduction of average values for certain cost components in order to reduce the calculation effort (Riebel, 1994b). However, Riebel transfers the responsibility for these decisions to the cost accountant(s) in charge. Moreover, he refers to Schneider (1972), who writes about this balancing act. On the one hand, the calculations should be practicable and efficient, thereby allowing a certain degree of inaccuracy (Schneider, 1972). On the other hand, according to Schneider, this is exactly the task of the accountant(s): to determine the degree of inaccuracy resulting from deliberate simplifications such as assumptions. He instances and contrasts the field of operations research, which he criticizes for putting the calculation method above its application in practice, which is a wrong priority in Schneider's (1972) opinion. In an analogous manner, Riebel (1994b) accuses the field of accounting of the same mistake and therefore calls for an implementation- and practice-oriented approach.

2.5.4.4 Exceptions From the Identity Principle

With the highest caution and awareness possible, a cost accountant can disregard the identity principle in specific situations (Riebel, 1994b). Contrary to the strict application of the identity principle, overhead costs can be allocated to cost objects for specific purposes and questions (Riebel, 1994b, p. 78, own translation from German):

- The necessity of transfer prices in joint ventures for delivered or purchased goods or services
- The distribution of joint costs in joint ventures in order to quantify each party's profit share
- Company-internal questions such as the preliminary order costing of a large number of small orders

In these cases, it should be verified that there is no other cost allocation key or principle that is more specific and hence appropriate for the given question. Only then is it acceptable to disregard the identity principle by allocating overhead costs for the given purpose. Moreover, Riebel (1994b) argues that although the prevalent accounting approaches may appear more straightforward at first sight, their results are arbitrary and could be misguiding (Riebel, 1994b). He concludes the article with the claim that his new approach leads to correct results that enable better corporate decision-making and management support, which was the new aspiration at that time (Riebel, 1994b).

2.5.5 Critical Assessment of Riebel's Generic Direct Costing and Contribution Margin Accounting

Riebel's Generic Direct Costing and Contribution Margin Accounting represents an indispensable part of the development history of the field of cost accounting. Although it stood in contrast to other cost accounting approaches, it pursued the exact same goal, namely offering informed and reliable decision support. It challenged the academic discourse and led to a controversial debate at that time, thus fostering critical thinking. Riebel's own critical reflection will be taken up and quoted towards the end of this subsection.

A central insight is that Riebel's cost accounting system focuses on expenses and not on costs, thereby laying the ground for internal corporate accounting (Küpper, 1994). Moreover, this shift of focus is important for the whole accounting discipline because it changed the meaning and thus increased the importance of cost and performance accounting (Küpper, 1994). Although Küpper (1994) did not immediately understand Riebel's body of thought, he attested that this approach has increasing value over time as he continued to overlook its consequences and application possibilities such as its meaning for management decisions and investment calculations. Kilger also ascribes high theoretical quality and maturity to Riebel's costing system. Building on the identity principle and its consequential implementation, he finds it to be thought out and scientifically sound. Although it may enable valuable food for thought for the improvement of sales controlling activities, Kilger (1993) cannot find value for corporate practice and recommends his own approach: "[…] consequently designed cost-center and cost-carrier oriented flexible standard costing" [own translation][13] (Kilger, 1993, p. 86). Despite his opposing view, Kilger (1993)

[13] Own translation, original in German: "[mithilfe] einer konsequent ausgestalteten kostenstellen-kostenträger-orientierten Grenzplankostenrechnung besser erfüllen" (Kilger, 1993, p. 86)

includes a chapter about Riebel's cost accounting approach in his monograph. He points out that Riebel suggests several novelties and differences compared to the usual cost accounting approaches. Kilger evaluates Riebel's approach as follows:

First, Riebel introduces a purpose-neutral accounting database (cf. Subsection 2.5.2) and thus questions the division into cost type, cost center and cost unit accounting (Kilger, 1993). His approach allows a great number of cost objects and time periods following a hierarchical order. Costs are only allowed to be allocated to different cost carriers if unambiguous technical or statistical relationships exist (Riebel, 1994b). Kilger argues that Riebel's approach misses the valuable cost-unit relationship, which other cost accounting systems offer (Kilger, 1993).

Second, Riebel's identity principle redefines the terms *direct costs* and *real overhead costs*. This distinction cannot be made universally, but it is only applicable to a specific cost object according to his definition (Riebel, 1970). Depending on whether a specific cost component can be led back to the cost object—and only that specific cost object—it is considered *direct*. If that is not the case because there are, for example, other cost objects involved as well, they are categorized as unspecific or real overhead costs. As a result, costs can be direct costs and overhead costs at the same time because they are viewed from multiple perspectives simultaneously. Additionally, he introduces the term *readiness costs*, i.e., the expenses that are required to start production in the first place (Riebel, 1994a). This differentiates *Riebel's Generic Direct Costing and Contribution Margin Accounting* from marginal costing approaches such as *direct costing*, and it may confuse users since these definitions are not congruent with the common use of the terms at that time (Kilger, 1993). Kilger evaluates this as problem for the practical application of Riebel's approach (Kilger, 1993). The two professors Pfaff and Troßmann (2016), who are still active in the 21st century, attest that Riebel is the more consequential logician of the two, but they also criticize him for not building on the theories and definitions existent in the cost accounting field at that time. With regard to the neologism *identity principle*, Kilger (1993) argues that it was not necessary to introduce this new term to the cost accounting field because it was merely an interpretation of the causation principle. Furthermore, Kilger (1993) finds that although the attribution criterion of a specific decision may be theoretically correct, there are many indirect relationships and connections between costs or consumption volumes that lead to decision-making chains, making the application of this criterion in practice at least challenging. As mentioned above in Paragraph 2.5.4.2, Riebel points out that the identity principle is not a theoretical exercise, but in fact an interpretation of the causation principle that is of high practical relevance (Riebel, 1994b). Thereby, he strived to prevent critique due to misunderstandings of his cost accounting system. Interestingly, Riebel includes the viewpoint of scholar Kilger in his paper and points out that the identity principle had been approved by Kilger in 1976. However, Kilger's understanding of the principle is not as strict as Riebel's (1994b) original definition. Moreover, Riebel points out that his interpretation of the causation principle that views decisions as the root cause of costs had not yet been understood in the cost accounting field at that time (Riebel, 1994b).

Third, the identity principle classifies costs as overhead costs if they cannot be led back to the same decision, although they may be proportional to corporate performance. Hence, many cost components cannot be allocated to specific products such as logistics, maintenance and social costs (Kilger, 1993). Taking up the example of maintenance costs again, Riebel (1994b) argues that the decision to make a production factor available for production activities in the future is the true cause of these costs (cf. Paragraph 2.5.4.2), Kilger's approach follows the line of argumentation that the maintenance costs grow proportionally with the use of the production factor, i.e., they should be allocated to the products, for example, via operating hours (Kilger, 1993). Although Riebel was a chemist and strived for more accurate decision support with his approach, it can yield a high total of overhead costs, hence leading to a relatively small sum of direct costs, particularly in chemical production processes, thereby weakening the information content for corporate decisions (Arbeitskreis „Deckungsbeitragsrechnung" im Betriebswirtschaftlichen Ausschuss des Verbandes der Chemischen Industrie e.V., 1972). In his response to this shortcoming, Riebel suggests the allocation of these cost components, which Kilger criticizes as inconsistency in Riebel's approach (Kilger, 1993; Riebel, 1994b).

Another point of criticism is that Riebel's cost accounting system based on the identity principle does not structure costs and business performances in time periods such as months. Consequently, it is not necessary anymore to differentiate between decisions affecting the short term or the long term. Long-term decisions are usually supported by investment calculations, which consider a longer time horizon (Kilger, 1993). There are direct costs and overhead costs for the different time periods, which can, for example, be a shift, a day, a month, a quarter or a year. However, the identity principle prohibits the distribution of overhead costs for monthly analyses if they do not refer to that month already. For example, depreciations cannot be included in monthly analyses anymore (Kilger, 1993; Riebel, 1994b).

In order to enable the calculation of net profit within a given time period, Riebel suggests a framework based on accrual accounting and additional calculations that take care of the cost components that cannot be subsumed under the mentioned framework. The additional calculations are called *period-overlapping accounting* ("Zeitablaufrechnungen" in German) and they include time-related aspects of the costs such as dates of payment or notice periods (Riebel, 1994b). Kilger (1993) criticizes this alternative as "complicated system" [own translation][14] (Kilger, 1993, p. 81). Moreover, he does not agree with Riebel's suggestion to not periodize readiness costs. Albeit this results from the identity principle, it is not consistent with the other economic processes taking place in a business company (Kilger, 1993).

Moreover, Riebel's approach comprises a cash-flow based analysis, which Kilger (1993) does not consider a component of cost accounting, but a detached accounting system instead. He argues that cash-flow analyses follow a different structure (Kilger, 1993). To monitor a company's liquidity, the different cash flows need to be registered, which can disturb the analyses with regard to cost centers and cost carriers (Kilger, 1993).

Riebel's approach can also be found in the US-American cost accounting community, and it was suggested by Nielsen (1954), a professor for business administration at Standford University. However, according to Shillinglaw (1961), this approach was not successful for the following reason: "This simplifies or even eliminates the cost allocation problem, but it also produces profit contribution data that may be grossly misleading" (Shillinglaw, 1961, p. 261). This could be caused by the risk of misunderstanding the approach, which does not include all cost categories (Kilger, 1993). Interestingly, Kilger (1993) points out in a footnote that Nielsen's publication (1954) is not included in Shillinglaw's later work anymore.

In *Riebel's Generic Direct Costing and Contribution Margin Accounting*, Riebel (1994b) himself states that his cost accounting system was "fundamentally different from all other existing cost accounting systems" [own translation][15] (Riebel, 1994b, p. 1). Consequently, it was questioned by advocates of the alternative systems. However, Riebel addresses points of criticism surprisingly on page two by naming potential barriers that hamper the adoption of the system including IT-based requirements such as the extension of master and transaction data. Another potential barrier he states is of human nature and represents habitual hurdles because it requires the breaking with traditional rules. Hereafter, Riebel (1994b) opposes that first of all, his research had been

[14] Own translation, original in German: "kompliziertes System" (Kilger, 1993, p. 81)
[15] Own translation, original in German: "[…] ein Konzept, das sich grundlegend von allen anderen Systemen der Kosten- und Leistungsrechnung unterscheidet" (Riebel, 1994b, p. 1)

empirically tested and implemented in a corporation from the beginning, followed by further companies, albeit in a simplified version. Second, the performance of operational hard- and software, including data generation and handling, had been growing substantially over the preceding years, making cost analyses easier and faster (Riebel, 1994b). Third, Riebel acknowledges that his system challenges the current way of thinking and the corresponding habits. He then argues that on the one hand, his system was compatible with existing software installations such as the software package SAP-RK and on the other hand, his system could be integrated in already existing installations that are based on a direct costing approach (Riebel, 1994b). Riebel closes his article "Core Features of the 'Einzelkosten- und Deckungsbeitragsrechnung'" with the following critical conclusion:

> The main problems of introducing the concept are not the transposition of the organization or the implanting of new EDV [electronic data processing] programs. The main problems are the turnaround of thinking, the change of mind in the heads of all staff who have to use this concept. (Riebel, 1994a, p. 539)

Since Riebel did not show any spirit of compromise, he "[…] almost seemed to be the 'papal dogmatist'" [own translation][16] (Küpper, 1994, p. 41). Other subject matter experts find that he is consequential in his approach (Pfaff & Troßmann, 2016). J. Weber and Weißenberger (1996) published a research paper in English titled "Relative Einzelkosten- und Deckungsbeitragsrechnung: A Critical Evaluation of Riebel's Approach". They came to the differentiated conclusion that Riebel's accounting system "will presumably never be fully implemented in practice" (J. Weber and Weißenberger, 1996, p. 27) on the one hand. On the other hand, in their opinion, it provides important ideas for the development of existing and new accounting systems, and it is of high value for academia (J. Weber & Weißenberger, 1996). Undoubtedly, the practical dimension of cost accounting is essential, and its application should always lead to additional value for the company. Notwithstanding this statement, theoretical reflections on the discipline of cost accounting and its evolution can support its understanding and foster its further development. Therefore, Riebel's body of thought—even though it may be particularly academic—has been valuable for the advancement of cost accounting theory and can thus provide useful impulses for the advancement of the MFCA method.

2.6 The Meaning of Kilger's and Riebel's Cost Accounting Systems in Retrospect

The development of the cost accounting discipline from absorption costing to the different forms of direct costing represents a quantum leap. It did not only change the way the different cost categories are handled, but it decided to exclude certain cost categories, which was a revolutionary step (Kilger, 1993). This paved the way for a decision-oriented application, and it changed the viewing direction of the discipline. Kilger's (1993) first chapter covers the historical development of cost accounting over time. Although Kilger and Riebel were two passionate and eminent personalities, it becomes clear that there were many parallel currents and that many people worked on the questions and demands company management was facing at that time. Moreover, continuous debates nourished the development, and promotion and support activities including conferences and training programs such as N.A.C.A., NAA and AGPLAN paved the way from theory into practice.

[16] Own translation, original in German: "[…] schien er mir fast der „päpstliche Dogmatiker" zu sein" (Küpper, 1994, p. 41)

When comparing Kilger's and Riebel's accounting systems, it is important to remember that they were both striving for the goal of finding the correct cost accounting approach (Pfaff & Troßmann, 2016). Both systems contain aspects of vital importance. The fact that they struggled and corresponded with each other and further professors of their field should not be underestimated. It fueled the further development and thus most likely increased the quality of their work (Pfaff & Troßmann, 2016). While Kilger's key aspect is proportionality, Riebel's key aspect is a decision. These criteria lead to different understandings and definitions of direct costs and overhead costs, and thus to different calculation results. Kilger (1993) attests Riebel's approach a high level of correctness and logic, but considers its value reserved for academia and not for industrial practice. Plaut and Kilger cooperated as research partners and hence built a strong connection between theory, academia and practice. Undoubtedly, their activities surrounding their approach in the form of training and networking events also promoted the dissemination of their ideas.

What makes the debate between Kilger and Riebel interesting from a scientific point of view is Kilger's wording in his critical reflection of Riebel's approach in subsection 1.344.1 in Kilger's book. When arguing against Riebel's approach and trying to refute it, Kilger uses the wording "we believe" [own translation][17] (Kilger, 1993, pp. 84–86) three times. The verb is used to express that, on a personal level, Riebel's pathway is not considered the correct approach. Instead, Kilger regards another pathway as (more) accurate in his opinion (Kilger, 1993). Moreover, he agrees with the evaluation of Käfer (1964) who rejected the consideration of payment transactions (Kilger, 1993). These observations are insofar meaningful that the statement does not immediately address or attack Riebel's line of thought, but rather points out and recommends an alternative pathway, which should be preferred in Kilger's (1993) opinion. For this reason, this line of argument does not automatically falsify the other approach. It is rather a matter of different perspectives.

The working group for internal cost accounting of the Schmalenbach Society has included both Kilger's and Riebel's main work—together with 16 other classics—in their publication "Pillars of Cost Accounting" [own translation][18] (2017). The working group emphasizes that Kilger wrote a comprehensive and structured monograph, while Riebel's rather complex cost accounting system was published first in single articles that were later published in a compilation of the articles (Franz, 2017a, 2017b). This difference may have influenced the understanding of the two approaches in practice and hence their application in practice. Moreover, the working group ascribes Kilger in comparison to Riebel a larger influence on cost accounting theory and practice, and its implementation in software products promoted its success in corporate practice (Franz, 2017b). Nevertheless, Kilger's approach with its annual plan calculations became outdated with the acceleration of the economy, and the adaptation of the approach to this dynamic development was not accepted in academia nor in corporate practice (Franz, 2017b). Taking a look at a German cost accounting book published in its fifth edition in 2023, Riebel's name is absent, while Kilger's and Plaut's (team)work is mentioned in a chapter on historical development (Horsch, 2023).

These insights and findings offer valuable food for thought for the methodological advancement of the MFCA method, which represents the core of this thesis. The different approaches to cost accounting pursued the common goal of improving cost accounting in a way that serves its end users by providing useful cost accounting results. In a similar way, MFCA aims to improve the resource efficiency of corporate production processes by pointing out and analyzing material losses. Just like cost accounting was developed and refined over time in order to better

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[17] Own translation, original in German: "wir glauben"—"we believe" (Kilger, 1993, pp. 84–86)

[18] Own translation, original in German: *Säulen der Kostenrechnung* (Arbeitskreis Internes Rechnungswesen der Schmalenbach-Gesellschaft für Betriebswirtschaft e.V., 2017)

serve corporate management, MFCA 2.0 represents an advancement that strives to improve and support corporate decision-making.

2.7 The Case for Activity-Based Costing and Process Cost Calculation: Further Steps Forward

Interestingly, the development of activity-based costing (ABC) in the US paved the way for the development of process cost calculation in Germany, and they both integrated all costs components again, including overhead costs. ABC was initially developed in the US by Cooper, Johnson and Kaplan (Cooper & Kaplan, 1988, 1991; Johnson & Kaplan, 1987), who built their work on existing ideas and findings on the topic of overhead costs that had been published by Miller and Vollmann (1985). Johnson and Kaplan (1987) then laid the ground for activity-based costing with their book titled *Relevance Lost: The Rise and Fall of Management Accounting*. The authors criticized the state of management accounting at that time and called for large changes in practice (Drury, 2012). Their line of argument can be summarized with the following quote by Cooper and Kaplan (1988):

> Virtually all of a company's activities exist to support the production and delivery of today's goods and services. They should therefore all be considered product cost. And since nearly all factory and corporate support costs are divisible or separable, they can be split apart and traced to individual products or product families. (Cooper & Kaplan, 1988, pp. 96f.)

ABC was the result of US-American cost accounting history, and J. Weber (2019) is of the opinion that until then, it had clearly lacked validity and informative value compared to the developments made in Germany (J. Weber, 2019).

Nevertheless, the two Germans Horváth and Mayer (1989) based their work on ABC, but they focused on corporate service areas that are not directly related to the shop floor. The reasoning behind this decision is that process cost calculation was designed to support strategic decisions that are relevant for the longer term. The progress of industrial production processes had led to increasing automatization and decreasing production depth in Germany over time. This development caused an increase of fixed costs due to planning, controlling and monitoring tasks as business activities which cannot be directly related to the products (Kilger, 1993). This gradually undermined the significance and informative value of the direct costing approach, leading to wrong results and thus creating the need for another approach. As a result, the question of a just allocation of fixed costs to the products rose again. This time, the period of process cost calculation was rung in Germany (Horváth & Mayer, 1989). The main characteristic of process cost calculation is that cost drivers are processes instead of cost centers (Kilger, 1993). Overhead costs are equipped with cost drivers in order to allocate them in an accurate way, following the causation principle (Kilger, 1993). Coming from the era of direct costing, this represented an unexpected change in direction since process cost calculation was an absorption costing approach again.

Many different forms of process cost calculation were developed over time, originating from activity-based costing (e.g., Dierkes, 1998; Glaser, 1998; H. Müller, 1993; Reichmann & Fröhling, 1993), albeit further explanation would go beyond the scope of this overview. Nevertheless, it is worthwhile to point out the motivation for these developments. They were motivated by the wish to combine the advantages of the absorption costing approach with the advantages of direct costing in order to eradicate the disadvantages, respectively. This is a worthwhile endeavor, and the title of Kaplan's (1988) article "One Cost System Isn't Enough" aptly describes this idea. Practice-oriented research can start by analyzing the status quo, reviewing previous developments, and it should then look for new ideas and useful combinations to develop new approaches advancing the research field.

2.8 "German Cost Accounting" From an International Perspective

This section focuses on the development and accomplishments of "German cost accounting" from an international perspective. Although there is little research on its evolution and the causes, a possible explanation lies in the history of the country of Germany, which was marked by the feeling of fear of the future and of losing money as well as one's belongings (J. Weber, 2018). This may have generated the need for a data-driven and detailed cost accounting approach that quantifies different alternatives, thereby making them comparable in order to eventually reduce uncertainty. In their essay on the development of cost accounting, Pfaff and Troßmann (2016) argue and conclude that the achievements made in the German-speaking area are of high quality, relevance and therefore also impact, hence serving as blueprint for the international cost accounting community. For example, Kilger's approach is known as the "German cost accounting approach" and it has received international attention both in practice and in academia (e.g., Krumwiede, 2005; Krumwiede & Suessmair, 2008). In 2004, Offenbacker published an English translation of chapter 0 [sic] of the German textbook *Flexible Plankostenrechnung und Deckungsbeitragsrechnung* originally written and published by Kilger in German. Offenbacker's translation is based on the 11th edition of the book, which was published 16 years after Kilger's death. This edition was completely revised and adapted by Pampel and Vikas to the development state and standards of cost accounting that were relevant at that time (Kilger et al., 2002).

There is a notable number of publications in English dealing with the topic of accounting in Germany (Keys & van der Merwe, 1999; Krumwiede, 2005; Krumwiede & Suessmair, 2008; Sharman, 2003; Sharman & Vikas, 2004). The authors have analyzed the characteristics, implications and advantages of cost accounting practice in Germany, also dealing with *Kilger's Flexible Standard Costing and Contribution Margin Accounting* and *Riebel's Generic Direct Costing and Contribution Margin Accounting*. Based on the analyses in these publications, German cost accounting has the reputation to be more accurate and comprehensive compared to the approaches and practices of other countries. Companies based in Germany promoted and demanded a strong controlling culture, leading to a strong cost accounting department (Sharman & Vikas, 2004). The publications also clearly differentiate between financial accounting and management accounting (Sharman, 2003). Moreover, Luther et al. (2009) have investigated differences between British management accounting and German controlling in an empirical study, analyzing three case studies conducted in German companies. They came to the conclusion that there are fundamental differences such as a strong focus on budgeting and forecasting (Luther et al., 2009). However, the closer observation of the publications reveals that the numbers of journals and authors are limited. Moreover, the research has been mostly conducted empirically among companies based in Germany, leading to practice-oriented results and recommendations with regard to Kilger's cost accounting approach. This hypothesis finds support in the following four indications.

1. Empirical on-site research that was conducted in 2004 in German-speaking countries came to the conclusion that the German cost system *Grenzplankostenrechnung*, also known as *GPK*, is a form of flexible standard costing which "can be a big help to U.S. firms in making decisions and controlling costs" (Krumwiede, 2005, p. 34).
2. If upper and top management support the implementation of *Grenzplankostenrechnung*, it is much easier to make corporate resources available that are required for the successful utilization of *Grenzplankostenrechnung* (Krumwiede & Suessmair, 2008).
3. A survey on *Grenzplankostenrechnung* with 286 evaluable responses addressed three topics: stages of implementation also regarding information systems, usage and success factors such as support by top management and nonaccounting employees, and the combination of *Grenzplankostenrechnung* with other cost management methods (Krumwiede & Suessmair, 2008). The authors emphasize at the beginning and again at the end of their report that the respondents had successfully and satisfactorily established the *Grenzplankostenrechnung* system.
4. During his visit of six corporations in Germany and Austria, Sharman (2003) discovered that the number of employees of the management accounting departments is the same or even higher than the number of employees of the financial accounting departments. Moreover, these management accounting departments are determined to support corporate planning, decision-making and to control operations (Sharman, 2003).

An empirical study conducted together by an US-American and a German professor indicates that *Grenzplankostenrechnung* is practiced mainly in the following industries (Krumwiede & Suessmair, 2008, p. 38):

- Chemicals, paper and printing
- Wholesale and retail trade
- Construction and mining industries
- Machinery and equipment industry related to the automotive industry

Germany can be considered as "world champion in cost accounting" [own translation][19] (J. Weber, 2019, para. 3) and the following three reasons may have led to the specialization on cost accounting in this country. The article differentiates between the German- and the English-speaking world. The first reason may lie in the fact that financial accounting and cost accounting are not kept separate in English-speaking countries (Kilger, 1993; Sharman, 2003). German-speaking countries, on the contrary, keep the two separated from each other, which offers more freedom in implementation and practice, respectively (J. Weber, 2019). The second reason addresses the education system, which in the English-speaking world continues to shape accountants throughout their professional career (J. Weber, 2019). For example, in the US and the UK, there are many training programs aside from university education, which is not the case in Germany (J. Weber, 2019). Instead, J. Weber (2019) argues, university education and especially the close connection of business studies with production and cost aspects secured appropriate preparation of cost accountants for Germany's large industrial sector. The third reason lies in cultural differences. As a whole, German culture tends to address and reduce risk with the formulation of facts on a high level of detail (J. Weber, 2019). J. Weber (2019) hypothesizes that this may have incentivized the

[19] Own translation, original in German: "Weltmeister der Kostenrechnung" (J. Weber, 2019, para. 3)

development and adoption of detailed and complex cost accounting approaches, which at least partially were considered as complicated from international and perhaps even from some German-speaking viewers. The article closes with the following future perspective: While Kilger, Plaut and Riebel strived after an increase of occupancy rates to optimize profits, today's reality requires high flexibility in order to quickly adapt to market changes (J. Weber, 2019). The behavior and decisions of large companies are driven by the capital market and its rules, which in turn are defined by Anglo-American players in a largely globalized world economy (J. Weber, 2019). These players are not familiar with the cost accounting approach practiced in Germany, and they focus on cash flows and earnings before interest and taxes (EBIT) (J. Weber, 2019).

Consequently, German cost accounting has lost practical relevance from a global perspective. However, three aspects should not be left aside. First, this does not affect the accuracy and validity of its content. Second, just like in the fashion industry, the chances of a revival of these cost accounting approaches should not be underestimated. Third, the circumstance that large companies may be driven by the global capital market (J. Weber, 2019) does not contradict the advantages that Kilger's and Riebel's approaches offer, such as the increase of occupancy rates to optimize profits. Herein lies the cornerstone for this dissertation. MFCA is a special form of cost accounting, and the methodological developments and the analysis of the academic discourse that has been led by Kilger and Riebel in the last century have generated innovative ideas. These ideas bear the potential to increase the relevance of the MFCA method for corporate practice. In its current form, MFCA contradicts traditional cost accounting principles, as will be shown in this thesis in Section 3.6. Furthermore, it offers little support on the question of how to improve the processes analyzed with the method. Therefore, this thesis aims to lift the method on the next level, introducing it to a broader audience and thus making a practical and measurable contribution to sustainable development.

2.9 The Meaning of (Material) Losses in Cost Accounting—Hints for MFCA 2.0

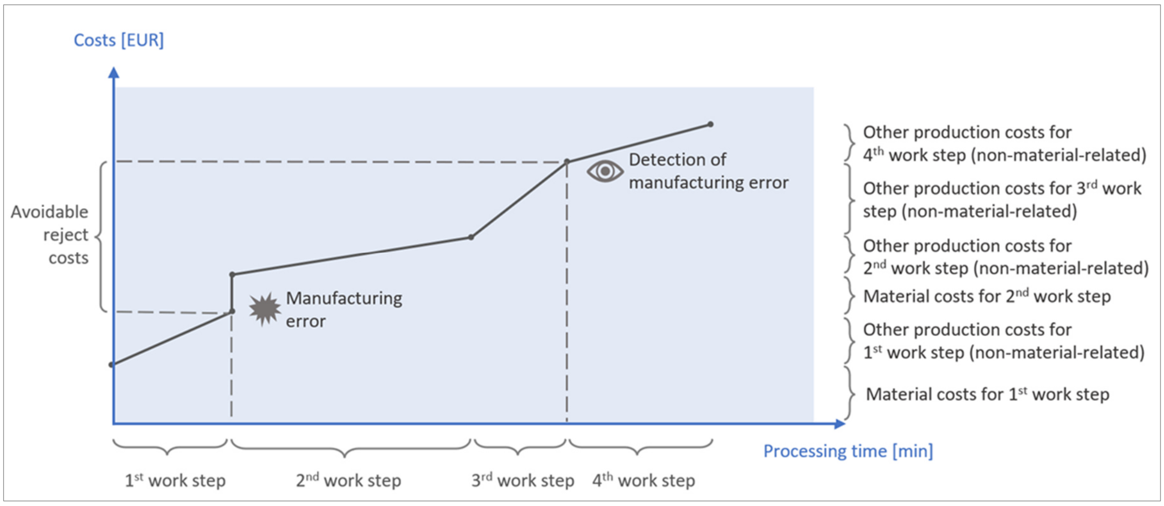
The explanations included in this section are going to approach the topic of cost accounting with a focus on losses and waste in order to lay the groundwork for the methodological advancement of MFCA. Kilger (1993) lists four different kinds of additional and unplanned quantities of material consumption in the engineering sector and comparable industries (pp. 243f., own translation from German):

1. Unscheduled blends and cuts:
   This can be the result of different sizes of the raw material such as metal sheets, bar or tube materials.
2. Unexpected or unplanned material qualities:
   If the planned material qualities are not in stock or available in the short term in order to produce and fulfill the order on time, available material of higher quality needs to be used.
3. Increased rejects:
   Rejects can be led back to errors in the production process or material defects.
4. Changes in construction or design:
   According to Kilger (1993), this is a frequent cause of additional and unplanned quantities of material consumption in the engineering sector and comparable industries, and it is of high relevance for long-term production because changes in construction or design cause

permanent additional material consumption and thus repeated discrepancies between planned and actual consumption volumes.

Rejects cause additional consumption volumes, and this relationship received increased attention, including the discussion of the planning and control of these additional costs (Kilger, 1993). First, rejects are defined as products that are not able to fulfill their intended purpose caused by insufficiencies. To increase the quality of the definition, Kilger (1993) draws on the works from W. Müller (1969) and Buchinger (1971). Based on their ideas, rejects are to be differentiated from waste, which are both quantities of material(s) that are inserted into a production process without being part of the final product. Waste contains material costs only, whereas rejects additionally contain manufacturing costs (Kilger, 1993). However, it is difficult to draw a line between waste and rejects in practice, especially in the case of flow production (Kilger, 1993). Furthermore, rejects are to be distinguished from products with defects that can be reworked and thus eliminated. There are also products with defects that can still be sold with a note about their decreased quality (Kilger, 1993). Real rejects, on the contrary, cannot continue their path along the planned production route towards the sales market, and the costs incurred until this point are categorized as reject costs (Kilger, 1993). Reject costs are a special case, requiring increased attention from the cost accounting department because it "[…] ranks among the most complicated specific problems in cost accounting" [own translation][20] (Kilger, 1993, p. 279). Kilger (1993) recommends adding up rework and reject costs due to their common cause(s). They can either still be turned into revenue following rework, the reject can be turned into revenue from scrap sales, or it remains a pure financial loss. The sum of rework and reject costs is composed of direct material costs, material overheads, production labor costs and production overheads (Kilger, 1993). If a direct costing approach is pursued, only the cost components proportional to the output quantity are considered (Kilger, 1993). The following Figure 6 illustrates the formation of reject costs.

Figure 6: Axis diagram depicting the formation of reject costs (Adapted from Kilger et al., 2012, p. 236, own translation from German)



[20] Own translation, original in German: "[…] zählt zu den kompliziertesten Spezialproblemen der Kostenrechnung" (Kilger, 1993, p. 279)

The diagram shows the direct production costs (y-axis) over time (x-axis). In the first and second work step, both material and other production costs are involved, whereas in the third and fourth work step, only non-material production costs are relevant. In the example, the reject was detected after the third work step and before the beginning of the fourth work step. Theoretically, the difference between the accumulated costs (y-axis) after the third work step and the costs that incurred in the first work step could have been avoided, as can be read off on the y-axis (Kilger, 1993). Kilger (1993) recommends repeated checks throughout the production process in case the probability of manufacturing errors and consequent rejects is high. This represents insofar a meaningful finding that part of the reject costs could have been avoided *although* the production error itself, which appeared in the first work step, was perhaps not avoidable. Furthermore, the concept of an unavoidable minimum rejection rate had been defined very early already and found further proponents decades later (Gillespie, 1935; Henrici, 1960; Käfer, 1964). However, Kilger (1993) critically remarks that data from the past should not be used as a basis since the data does not allow the differentiation between avoidable and unavoidable rejects and thus would lead to wrong results. Instead, the employees involved should be granted to define a realistic amount of production rejects (Kilger, 1993). In this context, realistic has the meaning that it presupposes a certain degree of attention and alertness of the production workers and a reasonable basis from an economic and financial point of view, which in combination define the probability to detect production errors early (Kilger, 1993).

Kilger (1993) suggests treating rework and reject costs as standard cost component. Moreover, this cost component can be registered and documented with a specific receipt which shall be complemented with an analysis that identifies the cost center and the employees involved (Kilger, 1993). There are two options how to process rework and reject costs in cost accounting. First, they can be processed within a specific product order, production batch or production series (Kilger, 1993). Once a production error has been detected, it should be examined whether rework is reasonable from an economic point of view, i.e., whether the direct costs of rework are smaller than the contribution margins of the final product. The second option includes factor inputs that take account of rejects and thus include these in the quantity structure for production planning (Buchinger, 1971). Buchinger (1971) recommends this for flow materials as it is the case in the textile or food industry since the delimitation of a single product order, production batch or production series would be difficult in practice. Therefore, the input factors are larger than 100% to make sure that the rejects are included in the planned quantities and thus also in the standard costs. Its reciprocal indicates the output quantity, and it is an efficiency indicator (Kilger, 1993).

When quantifying direct costs, Kilger (1993) suggests analyzing and thereby managing the waste quantities. Against this background, *net consumption* and *gross consumption* are defined, and their difference evinces the waste volume (Kilger, 1993). When analyzing the waste volume, a differentiation between avoidable and unavoidable waste is recommended (Kilger, 1993). Moreover, technical calculations and analyses should be preferred over statistics and actual consumption rates to reduce the risk of accepting inefficiencies that could actually be reduced (Kilger, 1993). Additionally, every waste should be annotated with a cause. As a result, the planned consumption rates and thus also the planned cost calculations take account of inefficiencies due to waste. This can be documented as follows (based on Kilger, 1993, p. 234, own translation from German):

	Net planned direct material quantity
+	Planned waste quantity, cause 1
+	Planned waste quantity, cause 2
+	Planned waste quantity, cause 3
+	…
+	Planned waste quantity, cause n
=	Gross planned direct material quantity
x	Planned price factor
=	Gross planned direct material costs

In a second step, this calculation can be complemented with material overhead and revenues generated when selling the waste, if applicable (Kilger, 1993). These results flow into a cost report, which is then communicated with the different departments of the company. It contains a summary of the cost analyses including the discrepancies between planned and actual costs as well as the cause information. Kilger (1993) instances how industries like the engineering sector deal with these discrepancies. Unplanned material quantities are to be documented with a special stock requisition that allows to track the additional quantities (Ellinger, 1954). The stock requisition should be marked in color, thereby being visually distinguishable at first sight, and it demands a written explanation for the additional material consumption (Kilger, 1993).

This represents an important basis for clear documentation and goal-oriented communication in order to increase transparency and to lastly reduce the discrepancies, which can be utilized for the development of MFCA 2.0. Once the value of unavoidable rejects has been defined, deviations from the actual values can be determined and put up for discussion (Kilger, 1993). In doing so, particular accuracy and caution are required when searching the causes of the deviations because the corporate work atmosphere will be highly sensitive to this topic (Buchinger, 1971).

Riebel's (1994b) cost accounting system does not directly address losses or waste, but it does contain information on how to handle different cost components. While the identity principle identifies and allocates costs to the cost object under analysis, the following three guiding questions are provided in order to classify and handle the different cost components (Riebel, 1994b, p. 280, own translation from German).

1. What costs are dependent from the nature and quantity of the product and will disappear if the products are eliminated?
2. What stand-by costs could be reduced if the products were eliminated from the product line for good?
3. Which of these costs would continue to accrue?

These three questions are of high value with regard to the methodological advancement of MFCA, and they can be applied to the product-loss distinction, thereby improving the method's decision-orientation. So far, MFCA has focused on the value related to the losses, whereas MFCA 2.0 strives to quantify saving potentials related to different decisions, as will be shown in the following Chapters 3 and 4.

There are also indications in the literature regarding the causes of losses. In 1920—i.e., more than a century ago—the US-American institution named Federated American Engineering Society identified the meaning of inefficiencies in production processes caused by waste. It commissioned a study on the topic of *Waste in industry* (Federated American Engineering Societies, Committee on Elimination of Waste in Industry, 1921), yielding the following causes of waste (Peters, 1927, pp. 97ff., cited after Kilger, 1993, own translation from German):

1. Losses due to wrong operating instructions 50–81%
2. Losses caused by workers 9–28%
3. Losses due to external circumstances 9–40%

These findings represent the beginning of corporate awareness regarding inefficiencies and fueled further investigations in the US and European industrial countries with regard to cost control based on planned costs, which then led to standard costing and flexible standard costing (Kilger, 1993). Kilger (1993) explicitly makes losses a subject of discussion in his cost accounting system and lists the following six causes, which are the result of the applied research activities of his research partner Plaut. They are a useful starting point of an improvement analysis (Kilger, 1993).

1. Uneconomic personnel deployment:

   This represents a major cause of economic inefficiency and especially if a task is not easily measurable, overstaffing is a likely phenomenon. Kilger (1993) instances case studies in which organizational changes, declining capacity utilization rates or exaggerated supervision of the production processes revealed large financial saving potentials.

2. Uneconomic energy use:

   This aspect is also encountered frequently in corporate practice. It first of all includes the energy type such as electric energy, gas and oil, which should be put up for discussion. Second, insufficient insulation of pipes can lead to energy losses and third, the power units are sometimes not chosen adequately with regard to the energy demands.

3. Uneconomic processes and workflows:

   This third cause of losses that is prevalent among industrial companies addresses circumstances of the production processes that can be improved through organizational or rationalization measures. Oftentimes, these measures are inexpensive and easy to implement, thus making them more worthwhile regardless of a company's individual structures and circumstances.

4. Uneconomic use of tools:

   In production processes, tools are sometimes used in an uneconomic way. For example, although the replacement of tools in use may increase the performance of the production machine, there is an optimum period of use that reduces the tool replacement and maintenance costs in the long run. Therefore, Kilger recommends defining and standardizing as well as communicating and monitoring these processes.

5. Uneconomic material usage:

   This cause covers many different aspects, as explained on the previous pages. The example that Kilger (1993) uses here are aluminum chips which were stored outdoors, leading to corrosion, which in turn reduces the metal recovery rate. Although the solution in the form of a warehouse required an investment and recurring additional costs, for example, for heating, the net savings were positive.

6. Uneconomic use of means of transport:
   With regards to transport, measures that support the economic use of means of transport are the reduction of idle or waiting time. Moreover, the choice of means of transport should be questioned because in some cases, a less expensive option is available and sufficient.

To conclude the chapter, Kilger (1993) notes that the administration and sales departments should not be left out of the scope of the analysis. These departments can offer significant saving potentials, for example, in the form of personnel reductions as a result of rationalization measures or a reduction of overhead costs resulting from the elimination or reduction of insurances that are inadequate and hence unnecessary (Kilger, 1993).

A more recent textbook on cost accounting with a focus on corporate practice addresses the topic of material losses briefly and emphasizes three aspects (Horsch, 2023, p. 59):

- The material inserted in the production process minus material losses should be measured and reported in the form of a material efficiency indicator. Furthermore, the material losses are assessed with the purchase price(s) of the material(s).
- Disposal costs cover the different steps that are required from the registration of the material losses via their collection, transportation and treatment, if necessary, to the actual disposal.
- If production efforts lead to rejects that are not marketable, these efforts are to be accounted for as non-value-adding performance.

Finally, the costs related to material losses are accounted for as material costs (Horsch, 2023). However, Horsch (2023) explains that if materials are led in a closed loop within the production system under analysis, they are not to be accounted for as loss costs, although they are not included in the product. The subsection on material cost closes with the instruction to implement measures that reduce the material losses “to a minimum”[21] (Horsch, 2023, p. 59), such as the acquisition of new machines. First of all, this instruction is measure-oriented since it does not end with the disclosure and analysis of losses, but strives for an efficiency improvement of the process(es) under analysis. Second, the wording suggests that material losses can and should be reduced, but that they cannot always be eliminated. This goes hand in hand with the concept of an unavoidable minimum amount of loss, which Kilger (1993) has taken up from Gillespie (1935), Henrici (1960) and Käfer (1964). To exercise control over direct costs, Horsch (2023) also differentiates between planned and unplanned rejects and rework. He argues that the cost center manager should only be held responsible for unplanned occurrences of rework and rejects. For example, if the material quality was insufficient or short-term changes in the production sequence were decided, this may demand a restart of the machinery with new production settings, leading to additional production errors (Horsch, 2023).

Despite these detailed thoughts on the handling of losses in cost accounting, the saving potential related to the losses—neither in physical nor in monetary units—has not been discussed in research literature so far. However, the quantification of the saving potentials based on the potential loss reduction is an important step, enabling the evaluation and comparison of different improvement measures and hence providing decision support for management. Being a promising strategy for cost reduction and process optimization, it should be included in the advancement of

[21] Own translation, original in German: “auf ein Mindestmaß” (Horsch, 2023, p. 59)

the method. Finally, these different aspects provide multiple new ideas for the development of a more practice-oriented version of the MFCA method altogether.

2.10 Food for Thought From Cost Accounting for MFCA 2.0 and a Consulting Concept

The following ideas provide the basis for the consulting concept accompanying MFCA 2.0 that will be presented in Chapters 4 and 5. With its focus on material losses, MFCA goes hand in hand with the idea to control costs. The importance and need to control costs had already been phrased and published by Schmalenbach (1908) more than a century ago. It was the economic uncertainty following WWI that led to the development of planning and budgeting activities, which then revived the idea to control costs (Kilger, 1993). As has been stated before, Kilger and Riebel both disagreed with absorption costing, which was prevalent at that time, and they both pursued the goal to capture costs correctly and to make cost accounting more decision-oriented. In a similar way, MFCA can increase its significance by including decision-relevant aspects in MFCA 2.0. Although the method has been around for more than two decades, its popularity has remained rather low so far (Günther, Rieckhof, et al., 2017). The methodological advancement of this work aims to make production processes more transparent and hence to control and reduce costs and GHG emissions.

When conducting a cost analysis, Kilger (1993) suggests defining the cost deviations first that will be the focus of the analysis. This is comparable with a goal and scope definition that, for example, also precedes a life cycle analysis (International Organization for Standardization, ISO, 2006a, 2006b). One important aspect is that so far, MFCA has included all cost types when analyzing a production process. Just like in absorption costing, this approach can be misleading due to different time horizons (Günther, Rieckhof, et al., 2017). For example, in the short term, costs related to the size of the building or workforce cannot be reduced immediately and moreover, they cannot always be reduced linearly. In 1950—in fact parallel to the formation of the concept of direct costing—Stepf (1950) stated that the difference between revenue and cost per unit of production should only consider proportional costs. The two reasons are firstly, the simplification of the calculations and secondly, the increased informative value of the results for short term decisions (Stepf, 1950). This insight is transferable to the method of MFCA. The different cost types can be complemented with information regarding the time in which they can theoretically be reduced. MFCA 2.0 can process this information by taking only the cost components into account that are variable with regard to the time horizon associated with the question under analysis, thereby making the method's results more realistic and decision-relevant because these results are closer to the actual saving potentials than the results based on all cost types.

The historical overview of cost accounting already mentioned the presentation of Haas (1927) on the topic of US-American standard costing. His presentation included two important arguments with regard to the calculation and handling of standard costs. The first argument criticized cost accounting practice at that time for being too past-related, hence hindering its influence on the future (Haas, 1927). The second argument Haas (1927) uses is based on the ability of standard costing to analyze and to control costs in principle. However, Haas (1927) argues, the effective application of the standard costing approach requires economic planning. With regard to MFCA 2.0, these two arguments are helpful because the methodological advancement should also minimize these risks by being future-oriented and by incorporating economic planning.

Additionally, Kilger (1993) suggests differentiating cost types with regard to whether the cost center manager is able to influence the amount of the cost type at all. When quantifying and analyzing the differences between target and actual costs as ongoing cost control, only cost types that can be influenced in the defined time horizon should be used. This makes the results more realistic and hence more decision-relevant (Kilger, 1993). He points out the possibility to combine specific short-term variance analyses, e.g., on a monthly basis with quarterly analyses that include all cost types, qualifying it as a closed cost accounting system (Kilger, 1993).

A further useful aspect is that quantifying cost variances should never be the final goal of such cost analyses. "The variance itself is not a control, for costs are not controlled by compiling statistics about them" (Henrici, 1960, p. 253). Therefore, Kilger (1993) argues, cost variances are the basis for further analyses, cost reports and subsequent conversations. He also points out the possibility to financially incentivize the reduction of cost variances with awards (Kilger, 1993). The analysis of the cost variances should consider their causes, the course of time as well as information on the question whether the cost center manager can be held responsible or not (Kilger, 1993). The responsibility aspect has been addressed by Horsch (2023) as well. On the shop floor, engineers should be involved that have received a specific training on these topics in order to improve the quality of the analyses (Kilger, 1993). Interestingly, the information is added that notwithstanding necessary care, the analyses are going to contain mistakes that can be caused by the following aspects which the cost center manager should not be held accountable for (Kilger, 1993, pp. 601f., own translation from German):

- Costs that occur irregularly
- Account assignment errors
- Data entry errors
- Technical or organizational changes in the cost centers
- Other circumstances that lead to variances for which the cost center manager should not be held accountable

When generating the cost reports for the cost center managers as mentioned in Section 2.9, Kilger (1993) refers to Wright (1962) who recommends the principle of *management by exception* instead of an all-embracing report. Important exceptions, i.e., the largest cost variances, should be highlighted and explained with further information. To begin with, the reports can be generated on a monthly basis and additionally for a longer time period including illustrations such as diagrams in order to capture the broader picture of cost development over time. Following Henrici's (1960) statement, the figures and reports are just a means to an end, which is why the cost reports represent the basis for subsequent conversations. Kilger (1993) suggests that the responsible foremen, department directors, supervisors and managing directors meet on a monthly basis in order to both discuss the variances and to search for measures that improve the corporate cost structure on a factual basis.

Taking Riebel's cost accounting system strictly, it cannot be applied to the method of MFCA since the allocation of costs between product(s) and loss(es) is not in accordance with the identity principle (Prammer, 2009). Nevertheless, Riebel's ideas do not need to be discarded. On the contrary, they offer valuable food for thought that can lead to new pathways of thinking which in turn generate innovative approaches. More precisely, it fosters a different way of thinking by focusing on decision alternatives and the effects of these alternatives (Riebel, 1994a). Prammer (2009) combines Riebel's approach with the concept of environmental costs and flow costs, stating that the allocation of costs to material and energy losses clearly contradicts both the causation and the identity principle. Notwithstanding this finding, he concludes that the value of the additional information is worth the exception from the cost accounting rule because it quantifies the economic efficiency of the cost center, which in turn provides a decision-oriented information. Finally, Prammer (2009) suggests the term “material and energy loss costs” [own translation][22] (p. 259) instead of “flow costs”. However, it should be noted that Riebel’s cost accounting system did not only lead to content-related difficulties in understanding such as the cost-object based perspective, which in turn challenged the implementation in practice (cf. Subsection 2.5.5) (Kilger, 1993). Additionally, Riebel did not publish a monograph, but a compilation of his articles, which may have impacted the understanding of his thoughts (Franz, 2017a). Therefore, the methodological advancement aims to deliver a well-structured version of MFCA 2.0 including a comprehensible and clear description. Moreover, Riebel defined product bundles as actual decision variable, which makes the method more decision- and action-oriented. Once the cost object has been defined, the identity principle specifies what cost components are relevant for the calculations. This can be transferred to the method of MFCA by shifting the focus from losses towards decision alternatives, thereby providing better management support.

With regard to traditional cost accounting being established in corporate practice, MFCA does not need to be interpreted as opposition or competitor to traditional cost accounting, but rather as an addition (Günther, Rieckhof, et al., 2017). In principle, MFCA is able to provide decision support in order to increase the resource efficiency of a production process, for example, in the design and planning stage of a product. Finally, Günther, Rieckhof, et al. (2017) suggest allocating the cost of the losses to the product as well. Although their motivation is not stated explicitly in the article, they mention the avoidance of a second cost carrier when calculating the product cost, which is consistent with traditional cost accounting (Günther, Rieckhof, et al., 2017). This aspect is useful for the development of MFCA 2.0 since the method is not readily compatible with traditional cost accounting. In summary, these observations and findings are valuable for the development of MFCA 2.0 and the consulting concept accompanying the method. They provide a fertile ground that enhances the method’s practical orientation and impact in corporate practice.

[22] Own translation, original in German: “Material- und Energieverluste-Kosten“ (Prammer, 2009, p. 259)

3 The Method of Material Flow Cost Accounting: Measuring the Real Costs of Inefficiencies

There's no such thing as a free lunch.—Milton Friedman

MFCA is a method belonging to environmental management accounting and it aims to quantify what value is lost through waste. The method analyzes processes, in particular production processes, and captures them in a material and energy flow model. Based on the model, physical, economic and environmental losses can be identified and quantified.

3.1 Origins of the Method

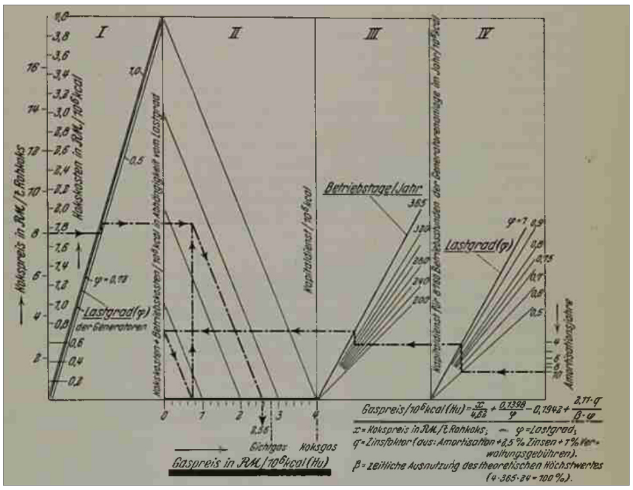
MFCA emerged from environmental management in Germany in the 1990s (Wagner, 2015; Wagner et al., 2010). After environmental awareness had moved from the technical focus of the 60s and 70s towards a more comprehensive understanding in the 80s and 90s, companies started environmental management projects in Germany. In 1991, one of the first corporate environmental reports was published and it was based on an input-output mass balance (Kunert AG, 1991, cited after Teichert, 1994), which in turn is the basic principle of the MFCA method. A documentation of the origins of the method can be found in Wagner (2015). Taking a step back, it can be noted that the input-output principle, i.e., the balancing of input and output flows within the scope of a company, is much older than the first corporate environmental report (M. Schmidt & Görlach, 2010). Its roots have been described and suggested by the German engineer Daeves in 1922 for the iron industry. Daeves argued that a company should account for its physical material and energy flows, including losses and production rejects, on a regular basis, just like the department for commercial accounting. Interestingly, he also mentioned the goal of the reduction of losses and production rejects against this background. Daeves' overarching goal was the development and use of a statistical method based on statistic frequency, which in turn required a solid database in order to scientifically monitor corporate activities (Daeves, 1922).

Rummel, another German engineer in the field of the steel industry, published an article titled "Influence of Business Thought Processes on Material Industry" [own translation][23] in 1936. It contains many ideas for a blueprint of the MFCA method, which are still of relevance today. The article proves the importance of economic principles in these early times, while nowadays, the fallacy that economic endeavors are a phenomenon of this time is widespread. Rummel requested an analysis of both physical, i.e., material and energy, and monetary flows, which should not be intermingled. The line of argument included reasons of resource scarcity and financial saving potentials, which are vividly illustrated with numerical examples and rough calculations (Rummel, 1936). This is congruent with the motivation of MFCA, being a method of environmental management accounting that combines economic and financial analyses. The corporate demand for professionals in that field is referred to as "a peculiar trend" [own translation][24] (Rummel, 1936, p. 222), which was already back then characterized as "more than a fashion" [own

[23] Own translation, original in German: "Der Einfluss betriebswirtschaftlicher Gedankengänge auf die Stoffwirtschaft" (Rummel, 1936)
[24] Own translation, original in German: "eine eigentümliche Zeiterscheinung" (Rummel, 1936, p. 222)

translation][25] (Rummel, 1936, p. 222), thus supporting Daeves' (1922) statistical approach. Interestingly, the German scholar Kieser published his view on management fashions six decades later. He critically reflects on the different purposes of management and gives research the assignment to question and analyze new developments and fashions (Kieser, 1996). Moreover, Rummel's article mentions the graphical representation of the Sankey diagram, which has become a widespread form of diagram, especially in the field of industrial ecology (M. Schmidt, 2008a, 2008b). With regard to MFCA, Sankey diagrams are a prevalent and popular display format in the field of industrial ecology (M. Schmidt, 2008a, 2008b). Furthermore, the article refers to a nomogram multiple times, which is an alignment chart that can be used for economic efficiency calculations. The advantage of this representation of the calculation results is that it can comprise many cases or scenarios in one diagram, thus supporting informed decision-making. Figure 7 shows an example of a nomogram, which contains the results for different assumed values, respectively.

Figure 7: Economic efficiency calculation as nomogram (Rummel, 1936, p. 227)



Rummel demands the breakdown and specification of losses into waste, melting loss and scrap material, and he makes the causes and measurement capabilities a subject of discussion (Rummel, 1936). Moreover, the method strives to analyze and categorize the losses and their causes in order to reduce the amount of losses. "Managing means choosing" [own translation][26] (Rummel, 1936, p. 226), representing the choice between different alternatives. These alternatives should be expressed in additional costs. To quantify the costs, all corporate units and persons involved should be consulted. Finally, the choice of a new installation should be followed by an examination after one year in order to verify the preceding assumptions and calculations (Rummel, 1936).

At the time the article was written, ecological impacts such as climate change caused by GHG emissions had not gained importance yet, which is why the material industry focused on economic values. In the meantime, environmental protection has certainly increased in importance and time criticality due to ongoing climate change. Nevertheless, it remains to be examined whether the method has developed from "a peculiar trend" [own translation][27] (Rummel, 1936, p. 222) into a management method prevalent and useful in corporate practice.

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[25] Own translation, original in German: "mehr als eine Mode" (Rummel, 1936, p. 222)
[26] Own translation, original in German: "Wirtschaften heißt „wählen“" (Rummel, 1936, p. 226)
[27] Own translation, original in German: "eine eigentümliche Zeiterscheinung" (Rummel, 1936, p. 222)

3.2 Concept of the Material Flow Cost Accounting Method

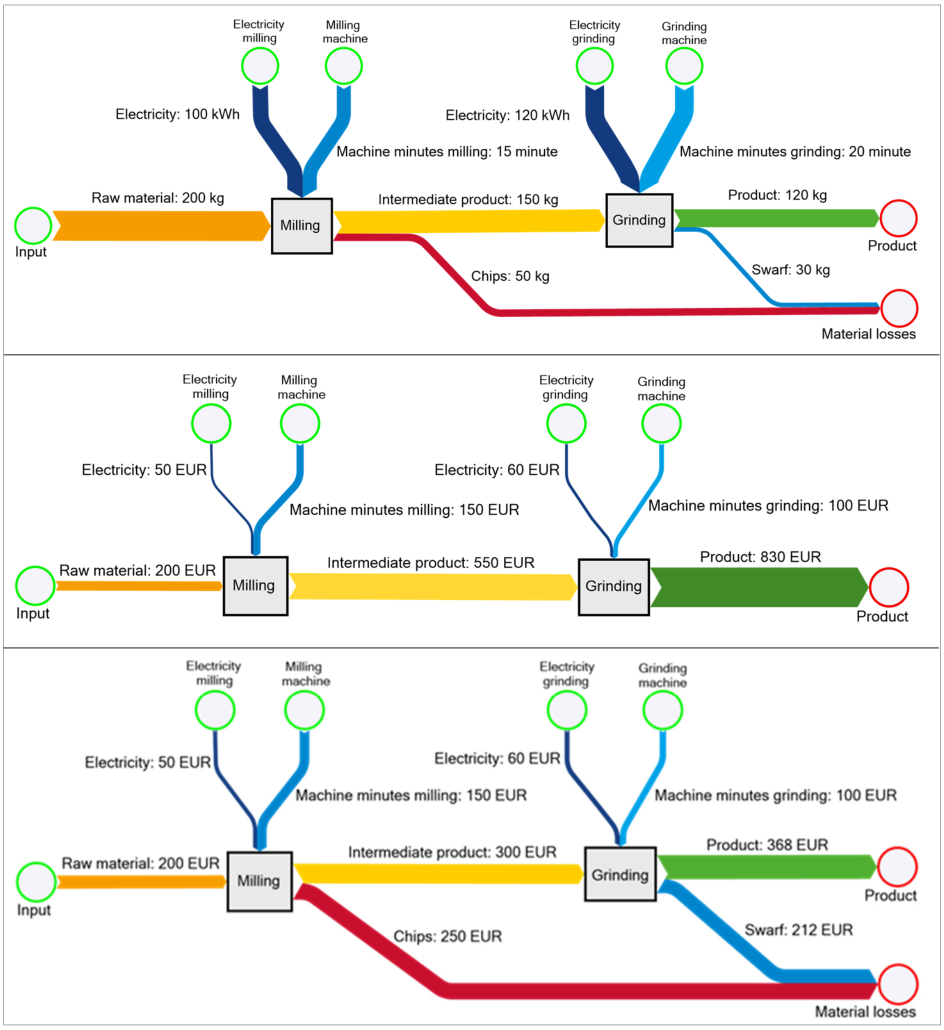
The core concept and an important strength of MFCA is the combination of economic and ecological endeavors, which are captured in an MFCA model of a selected product, production process or even a whole company. The model covers material and energy flows, and it arranges them in consecutive quantity centers (QCs), thus establishing a lucid structure. The model includes different kinds of losses such as defect parts, cuts or chips, recyclable material, but also exhaust gases, emissions or waste water. In a second step, costs are assigned to all flows in the model based on purchase prices and system costs for each individual process. The ISO 14051 differentiates between material costs, energy costs, system costs and waste management costs (ISO, 2011, pp. 13–17):

- Material costs (ISO, 2011, p. 15):
  Material costs accrue for substances entering and/or leaving a quantity center. There are multiple ways how to calculate material costs such as standard cost, average cost or purchase cost, and the company implementing MFCA can decide what calculation method they prefer.
- Energy costs (ISO, 2011, p. 13):
  This kind of costs accrue for media that provide energy including electricity, fuels, steam, heat and compressed air. Depending on the company's preference, energy costs can be subsumed under material costs or listed separately.
- System costs (ISO, 2011, p. 17):
  System costs can be led back to the processing and handling of materials that cannot be subsumed under the other three cost categories material, energy or waste management. Examples are labor costs, logistics costs or costs related to depreciation and maintenance of production facilities.
- Waste management costs (ISO, 2011, p. 17):
  These expenses are the result of material losses occurring in a production process and they can be related to solid, liquid or gaseous forms of waste including wastewater and air emissions. Waste management costs include the costs related to all activities that take place within and outside the company such as reworking of rejects, waste tracking or disposal.

Based on these cost categories, MFCA aims to quantify the physical and monetary values that are lost and the environmental emissions that are emitted due to these losses. The following Figure 8 shows the conceptual differences of conventional cost accounting and MFCA, which are both based on a physical material and energy flow model. At the top, material and energy flows are shown in physical units. In the middle, conventional cost accounting is depicted, which allocates all costs to the product. The model at the bottom presents the MFCA approach, which divides the costs between product and losses applying an allocation key such as mass in this example. The MFCA approach represents a new perspective because compared to traditional cost accounting, the cost related to the (undesired) losses becomes visible and awareness can be built. In this example, waste management costs of 3 EUR/kg occur for the loss flow *Chips* and 4 EUR/kg for the loss flow *Swarf*. The MFCA diagram (bottom) shows that the cost due to the material losses sums up to 462 EUR. That represents 55.7% of the total costs accruing in the process under analysis. This is the theoretical saving potential under the assumption that all material losses can be avoided.

Conventional cost accounting does not offer this perspective as it accepts the losses as given or unavoidable. Starting from here, measures to reduce the loss can be derived. With every kilogram the loss gets reduced, the total cost of the process decreases as well, and the values of its material and energy efficiency improve.

Figure 8: Examples of a material and energy flow model based on physical values (top), traditional cost accounting (middle) and MFCA (bottom) (Sankey diagrams created with *Umberto 11*® by iPoint-systems GmbH)



Rooted in environmental management and based on a physical model, a strength of MFCA as a special form of cost accounting is its focus on monetary values. This unique characteristic gives the method a bridging function between the economic and environmental dimension. It offers new perspectives and opens the eyes of management representatives and accountants insofar that material, energy and other input factors are not consumed in the strict sense. Rather, they are used and invested in order to achieve a desired outcome in the form of a product, together with undesired losses due to inefficiencies. The disclosure of these inefficiencies is then an incentive for the company to improve its processes. Möller (2010) points out the value of the physical model for cost accounting purposes and emphasizes the value of technical conversions, production units and structures. Another strength of MFCA is that it raises awareness for production processes and existing inefficiencies. This represents the perspective of the producer whose aim is to reduce the input for a given amount of output, e.g., by reducing losses, thereby increasing the process efficiency. This concept is rather straightforward and easy to understand. Notwithstanding, MFCA is a powerful and effective method that offers improvement potentials in two respects: First, its application in corporate practice can lead to the realization of improvement potentials and second, the method itself can be developed further, thereby realizing methodological improvement potentials.

3.3 Development of the Method in Germany and Japan and Its Application Around the World

A comprehensive documentation of the origins of MFCA has been written and published by Wagner (2015) in English and by Wagner et al. (2010) in German. This section will therefore only outline some highlights thereof. After the method had come into existence, research activities and many industry tests in German companies had proved its usefulness in practice (Wagner, 2015; Wagner et al., 2010). Although the dissemination of the method was strongly supported by the public sector, it petered out over the following years (Wagner, 2015). Through an international cooperation in which two Japanese professors were involved, MFCA found its way to Japan. The Japanese Ministry of International Trade and Industry (METI) supported the implementation of the method with the start of *The Environmental Management Accounting Project* in 1999. The project was followed by various activities such as a trial in the Japanese company Nitto Denko in 2000 (Wagner, 2015). Until 2010, between 200 and 300 MFCA projects were conducted (Wagner et al., 2010) and a Japanese METI report published 32 case examples (METI, 2011). M. Schmidt and Nakajima (2013) state that more than 300 Japanese companies have gained experience with MFCA at the time of the article's publication. In Japan, losses in production processes are referred to as negative products, while the actual products are considered positive products (Nakajima, 2004; M. Schmidt & Nakajima, 2013; Zhu et al., 2020).

The Japanese METI requested the standardization of the method within the ISO 14000 family on environmental management since prices on the global markets for raw materials were continuously increasing (Wagner, 2015). This suggestion coincided with a discussion about resource efficiency taking place in Germany and at EU level at that time. Consequently, MFCA was called to mind and revitalized (Wagner, 2015). After international exchange and negotiation processes, the standardization was successfully completed in 2011 with the ISO 14051 (ISO, 2011). In 2017 and 2021 respectively, the standards ISO 14052 (ISO, 2017) and ISO 14053 (ISO, 2021) followed. The expectations from the ISO standards were high, and experts predicted that the implementation of the method would increase resource efficiency on a global scale (Wagner et al., 2010). They argued that the approach of the method and its implementation in particular in small and medium-sized enterprises (SMEs) would be quick and easy to understand and therefore, it should be appealing for external consultants as well. However, Wagner's (2015) report took stock of MFCA's development after its standardization in 2011 and found that the MFCA approach is used in the industry mostly due to subsidies. Moreover, Christ and Burritt (2015) open section 7.1. titled "Implications from existing research" in their article contrasting the continuing dissemination of the method with a limited understanding overall and the need for further research. It has also been described how MFCA can be extended with the dimension of environmental assessment based on mathematical algorithms (M. Schmidt, 2015). The algorithms outlined in the article could be implemented in software applications that are then able to calculate complex production systems including internal recycling loops, thus increasing the relevance and attractiveness of the method for companies (M. Schmidt, 2015).

In Germany, there is a number of published MFCA case studies (e.g., iPoint-systems GmbH; Kawalla et al., 2018). Moreover, the practical research project *100 Pioneers in Efficient Resource Management* expresses the interest in resource efficiency both from a corporate and from a state perspective, and it includes five MFCA examples (M. Schmidt et al., 2019). A comparative study focusing on MFCA publications in Japan and China in Japanese and Chinese, respectively, found 312 MFCA Japanese publications between 2002 and 2018. In China, 132 MFCA publications were identified between 2008 and 2018 (Zhu et al., 2020). A remarkable development is that annual publications in Japan dropped after 2012, while Chinese publications show a growing trend in numbers, giving the authors a reason to suggest "promising possibilities for Chinese firms to incorporate MFCA in their environmental protection and cost-cutting activities" (Zhu et al., 2020, p. 5). However, this forecast is difficult to verify in practice due to existing language barriers, albeit a strength of the referenced study is the focus of publications in the Japanese and Chinese language, respectively.

Besides Japan and Germany, MFCA case studies have been conducted in different countries such as China (Yang et al., 2021; Yang et al., 2017; Zhu et al., 2020), Iran (Mahmoudi et al., 2017), Malaysia (Sulong et al., 2015), Pakistan (Ahmed et al., 2024), South Africa (Doorasamy, 2016; Fakoya & van der Poll, 2013), Ski Lanka (Dunuwila et al., 2018), Taiwan (Y.-X. Wang et al., 2017) and Thailand (Chompu-inwai et al., 2015; Kasemset et al., 2015; Yagi & Kokubu, 2018), where one case study combined MFCA with lean management (Chattinnawat et al., 2018). There are also case studies from India (e.g., Sahu et al., 2021; Shah et al., 2018; Tailor et al., 2017). Herzig et al. (2012) researched environmental management accounting in South-East Asia and included two MFCA case studies that were conducted in the food industry in Vietnam and the Philippines, respectively. Moreover, a scholar analyzed how MFCA could improve the seafood processing company in Vietnam (Nguyen, 2018). A meta study analyzing 28 MFCA case studies published in nine countries found a strong tendency towards developing and emerging Asian countries (Tran & Herzig, 2020). The authors conclude with the hypothesis that MFCA is especially useful for the manufacturing industry. This tendency will likely be reinforced with the rising service industries and shrinking manufacturing industries in more developed countries (Tran & Herzig, 2020). Since many scientific publications are written in English, they are accessible to a large audience. The publications that are written in other languages can nowadays be easily translated using online translators, thus significantly reducing language barriers and paving the way for international research exchange. The ISO standard—which will be the focus of the following Section 3.4—is a meaningful example of such an international cooperation.

In summary, MFCA shows a certain degree of relevance in the literature. While Germany and Japan as the method's birthplaces have a significant number of publications and method experts, Asian countries with their large manufacturing industries seem to be on the rise regarding application examples such as case studies. Although case studies in particular represent only part of the MFCA activities and the method's overall development, this trend is visible in the relevant literature. Since MFCA shows a large potential for the manufacturing industry, the application of the method and related research activities should be supported in national economies with a focus on the manufacturing sector. It would be worthwhile to continue to monitor the development of MFCA application, even though it should be kept in mind that these figures merely cover the MFCA projects that are published and not the ones that stay undisclosed for diverse reasons. While communication and publication activities are undoubtedly beneficial for the dissemination of the method, they are not the only pillar required to ensure the success of the MFCA method in the future.

In 2015, the *Journal of Cleaner Production* published a special volume on the topic of MFCA. The editorial article emphasizes that one strength of the method is its standardization with the ISO 14051, but it also finds that there is improvement potential regarding the MFCA method, the theory behind it and its application (Günther et al., 2015). A more recent article took stock of MFCA's progress and implementation in corporate practice and 27 Japanese companies were interviewed (Kitada et al., 2022). The interviews revealed that MFCA was mostly used for a short period of time. One aspect leading to a short application period is the strong involvement of external MFCA experts. Moreover, the duration of the application period depends on whether MFCA is introduced at the operational or strategic level and to what extent the management level is involved and committed (Kitada et al., 2022). This explains why the sole application of the method and further publications, e.g., in the form of case studies, are not the only factor influencing the method's future success. Kokubu and Kitada (2015) also see large potential in the method's standardization, which the following section is going to cover. Moreover, they argue, in order to support the lasting implementation of MFCA in a company, it is vital to integrate the method into the present corporate management system. The method has more development potential, and it requires more research. That is why the aim of this research is the methodological improvement of the method and the development of an accompanying consulting concept.

3.4 International Standardization: ISO 14051, 140052 and 14053

In 2011, the ISO standardized the method for the first time with the international standard *ISO 14051 Environmental Management—Material Flow Cost Accounting—General Framework*, complementing the ISO 14000 family (ISO, 2011). Six years later, the second standard *ISO 14052 Material Flow Cost Accounting—Guidance for Practical Implementation in a Supply Chain* followed (ISO, 2017), which is also the focus of some METI case studies (METI, 2011). A third standard, *ISO 14053 Material Flow Cost Accounting—Guidance for Phased Implementation in Organizations*, focusing on MFCA implementation in small and medium-sized companies, was published in 2021 (ISO, 2021). While the standardization by the ISO is certainly a significant milestone for the method's dissemination and comparability of MFCA projects and their results, it does not guarantee its successful implementation. The ISO 14051 comprises 38 pages, and the main part of the standard comprises common terminologies, the objective and principles of MFCA, fundamental elements and implementation steps (ISO, 2011, p. 9). Chapter 6 of the norm lists and explains the implementation steps of the MFCA method (ISO, 2011, p. 29):

- Involvement of management
- Determination of necessary expertise
- Specification of a boundary and a time period
- Determination of quantity centers
- Identification of inputs and outputs for each quantity center
- Quantification of the material flows in physical units
- Quantification of the material flows in monetary units
- MFCA data summary and interpretation
- Communication of MFCA results
- Identification and assessment of improvement opportunities

The annexes offer several practical examples that aim to differentiate MFCA from conventional cost accounting (Annex A), explain cost calculation and allocation (Annex B) and present additional case studies (Annex C). The annexes fill more than half of the pages of the document. The ISO 14052 comprises 13 pages, focusing on the application of the method in a supply chain (ISO, 2017). It offers a framework that supports activities along the supply chain such as information sharing that can initiate an increase in material and energy efficiency. Prox (2015) points out the large potential that collaborations along the supply chain have, as the method is not limited to the corporate boundaries anymore. Oftentimes, the analysis of losses that have been identified within an MFCA project does not lead to improvements because the reasons and scope of action lie within the territory of a supplier or customer (Prox, 2015). The article also addresses the critical aspects of trust being a prerequisite of a transparent and successful collaboration and the challenge that comes with a potential unequal distribution of improvement potentials between the actors involved. The third standard on the MFCA method is ISO 14053. The 16-page document offers practical support for the implementation of the method in phases in organizations in general and in SMEs in particular. It can be understood as a supplement to ISO 14051, which may be too sophisticated, hence making it difficult for organizations to successfully implement the method. Therefore, the document offers a calculation approach including example templates, information on analysis and improvement, the implementation of MFCA results and a case example in the annex. Additionally, common terminologies and principles of the MFCA method are included.

The international standardization of the method undoubtedly represents a milestone for the method's development and an advantage for the method's dissemination and application in practice. Nevertheless, as mentioned in the previous Section 3.3, it did not lead to the expected success once the subsidies were phased out (Wagner, 2015).

3.5 Status Quo of the Method's Application and Its Meaning in Practice (2025)

Over time, a substantial body of research on the MFCA method has developed. As Section 3.3 showed, a significant number of MFCA case studies has been published, and it continues to grow (e.g., Bux & Amicarelli, 2022; Sahu et al., 2021). There is a growing number of MFCA case studies dealing with agricultural topics and food production. Examples include cucumber, tomato and bell pepper grown in greenhouses as well as coriander seed and soybean production (Dekamin & Barmaki, 2019; Dekamin et al., 2022; Dekamin et al., 2024; van Tuyll et al., 2022). Moreover, for example, Chinese scholars have applied the MFCA method to the sugar industry, which is a significant water pollutant (C. Wang & Fu, 2024). In Thailand, scholars combined MFCA with an internet-of-things approach and lean management to reduce water consumption and production costs in the beverage industry (Sodkomkham et al., 2024).

Besides application-oriented case studies, methodological research has been conducted (e.g., Christ & Burritt, 2015; Kokubu & Kitada, 2015). Christ and Burritt (2015) reviewed the MFCA literature extant at that point in time and concluded that there is a lot of activity in research and practice regarding the method. Moreover, they argue that there is unused development potential for the method and that "existing knowledge has been curtailed by what could almost be described as a one-dimensional mindset" (Christ & Burritt, 2015, p. 1388). Therefore, they formulate an agenda for future research and first question the focus on action-based case studies. Instead, they propose to explore the method from different perspectives and approaches such as theoretical research that asks new types of questions, which they find to be too rare (Christ & Burritt, 2015). After all, an international study published in 2016 concludes that a small three-digit number of companies around the world has adopted MFCA (Günther, Günther, et al., 2017). In Germany—

one of the method's countries of origin—it is still not well-known in academia (Günther, Günther, et al., 2017).

Furthermore, there is an on-going debate about the further development of the method and its use in practice, for example, in the context of environmental management accounting (Christ & Burritt, 2015; Günther, Rieckhof, et al., 2017; Schaltegger & Zvezdov, 2015; Walz & Günther, 2021). Various suggestions have been formulated how to extend and refine MFCA further, e.g., by including outputs in the form of revenues, considering the financial effects of investments and modeling energy flows (A. Schmidt et al., 2015). Rahayu et al. (2018) and Leiva et al. (2025) apply MFCA to evaluate and improve industrial symbioses, which represents an advancement in the application of the method. Researchers have also begun to explore optimization approaches (Seifbarghy et al., 2022), the combination of MFCA with methods like life cycle assessment (LCA) and life cycle costing (Bierer et al., 2015; Dekamin et al., 2022; Rieckhof & Günther, 2018). The integration of MFCA in a circular economy is also a relevant research topic (Dieterle et al., 2018; Nishitani et al., 2022; van Tuyll et al., 2022; Zhou et al., 2017). MFCA has been combined with an input-output model that differentiates fixed and variable costs in order to better track material and energy flows (Machka & Beran, 2024).

In recent years, research on MFCA was also conducted and published in the form of dissertations. An exemplary dissertation investigated the method in light of circular economy thinking and explored the relationship of MFCA with traditional cost accounting based on a survey and a literature review (Walz, 2022). As part of the dissertation, an article was published that examines and tries to resolve the controversies between MFCA and established cost accounting practice (Günther, Rieckhof, et al., 2017). It states that the method had so far gained little relevance in theory and practice and emphasizes that it could not substitute, but rather complement cost accounting (Günther, Rieckhof, et al., 2017). Another dissertation developed a corporate planning instrument building on the method of MFCA in combination with a value-added approach (Siepelmeyer, 2023). This was implemented in an MFCA system that focuses on production and cost theory (Dierkes & Siepelmeyer, 2019). The system requires the summation of costs following the cost categories material, energy, system, and waste management costs. It differentiates between efficient and inefficient costs and generates allocation rates for waste, rejects and reworking- or recycling-related outputs, respectively. Moreover, the authors draw on the work of Kilger et al. (2012) and point out the relevance of MFCA as marginal cost accounting system for short-term decisions.

Besides these theoretical and partly critical thoughts, the application of MFCA in practice substantially contributes to the accomplishment of the Sustainable Development Goals (SDGs) (Kokubu et al., 2023). The SDGs—defined, promoted and pursued by the United Nations—represent a focal point for global cooperation towards peace and prosperity for the people and the planet (UN, n.d.). In 2015, they were approved by all of the UN's member countries (UN, n.d.). First, MFCA pursues SDG *12 Responsible consumption and production* by ensuring sustainable consumption and production patterns. The four targets *12.5 Substantially reduce waste generation*, *12.3 Halve global per capita food waste*, *12.2 Sustainable management and use of natural resource*s and *12.4 Responsible management of chemicals and waste* are particularly relevant (Kokubu et al., 2023). Moreover, the goals *6 Clean water and sanitation*, *7 Affordable and clean energy* and *13 Climate action* can be pursued through the application of MFCA (Kokubu et al., 2023). Therefore, it is a desirable objective to make the method of MFCA more practice-oriented in order to accelerate the achievement of the SDGs.

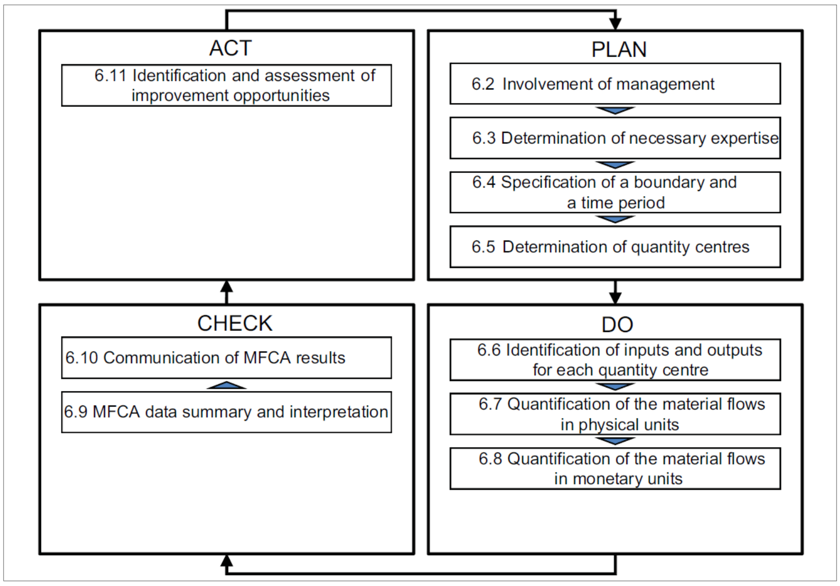
There is a number of specific software applications that support the implementation of the MFCA method. In Germany, the two largest applications are *Umberto*® (iPoint-systems GmbH) and the *Materialflusskostenrechner* (English *material flow cost calculator*) which was developed by The Association of German Engineers (VDI Technologiezentrum GmbH). The former is available in English as well, the latter is available in German only. *Umberto*® is a licensed and commercial software application that can be obtained from iPoint-systems GmbH (n.d.). Additionally, there is a cooperation in the State of Baden-Württemberg with the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg. This cooperation brought forth an offer of a reduced version of the *Umberto*® software free of charge for companies located or headquartered in the State of Baden-Württemberg. This software is called *bw!MFCA*. Additionally, Umwelttechnik BW—the State Agency for Environmental Technology, Resource Efficiency and Industrial Climate Protection in Baden-Württemberg—offers regular trainings and software support free of charge (Umwelttechnik BW GmbH, 2025). The material flow cost calculator by VDI is available as online tool and as smartphone app *ZRE Rechner* (VDI Technologiezentrum GmbH). These software applications offer valuable support when calculating an MFCA model, leading to more transparency about material losses and the amounts of energy associated with them. The software applications calculate the monetary losses related with the material losses in accordance with the steps specified in the norm ISO 14051. Finally, the ERP software *SAP S/4HANA*® (SAP SE, n.d.) may be capable to support MFCA to a certain extent by providing data on waste quantities and the related costs based on purchase prices. However, at the point of writing, no specific information regarding MFCA could be found.

In summary, the method of MFCA has been playing a role in corporate practice in different forms such as case studies, software applications and also in academia. There is a body of literature presenting many application examples and practical experiences with the method on the one hand, which can contribute to the accomplishment of the SDGs, respectively. On the other hand, there are theoretical and conceptual publications that evaluate the method, looking at its history and the history of cost accounting. Finally, there are voices that strive for methodological refinements, putting MFCA into perspective with today's corporate needs such as the topics managerial decision-making and circular economy. Based on this review and these reflections, this dissertation strives to contribute to the improvement of the method, taking up aspects that will develop the method further in practical terms.

3.6 Reasons Why the MFCA Method Requires a Methodological Improvement

Although MFCA's reason for existence is uncontested, it has been shown that the method is not being used in corporate practice on a large scale yet. Cost accounting is an inherently practical research topic, and the results should always undergo a practical test, including the assessment from a company's point of view. However, there seems to be comparatively little research on the conceptual foundations and theoretical considerations of MFCA. This dissertation aims to contribute to the conceptual advancement of the method by looking for inspiration in the history of cost accounting. The core of the method has been standardized with the ISO 14051, 14052, and 14053 (ISO, 2011, 2017, 2021), and the following improvement potentials relate to these standards. First, the ISO standard states that the MFCA method follows the "Plan-Do-Check-Act (PDCA) continual improvement cycle" (ISO, 2011, p. 29). Figure 9 shows the PDCA cycle as depicted in the ISO standard.

Figure 9: PDCA cycle for MFCA implementation (ISO, 2011, p. 29)



However, the PDCA cycle is not fully implemented in the method yet because it does not ensure the actual reduction of losses. Although the integration of MFCA in a company needs careful preparation and precise implementation, the challenge is to keep the focus on the goal when it comes to the check and act stages of the cycle. It is demanding to define the scope, collect all the data and calculate the value of the losses. Nevertheless, MFCA's full potential and final goal have not been reached until the MFCA data has been prepared for improvement measures including the respective saving potentials and until the amount of losses has actually been reduced. To achieve this, it is necessary to first find suitable measures and second to implement them in the manufacturing environment under investigation. The ISO standard closes with section *6.11 Identification and assessment of improvement opportunities* (ISO, 2011, p. 37). Identification and assessment do not connote an actual improvement of the system under analysis. Finally, the standard gives a number of general ideas for measures such as a potential substitution of materials, the modification of processes, production lines or products, and it emphasizes the value of R&D activities (ISO, 2011). However, this is not sufficient because manufacturing companies need tangible methodical support regarding the evaluation and implementation of improvement measures. The ISO makes the following statements on its website: "However, detailed calculation procedures or information on techniques for improving material or energy efficiency are outside the scope of this International Standard" (ISO, 2011, p. 11).

On that basis, it can be argued that a more measure-centered application of the method is missing. Although the identification and quantification of losses are crucial prerequisites for improvements, MFCA must not stop there, but instead guide towards improvement measures and provide data that supports decision-making. Viere et al. (2010) close their article on MFCA with the statement that the method does not offer tangible improvement measures. This can be substantiated with the criticism that no empirical proof for MFCA's positive effect on resource efficiency as a whole has been developed and published yet (Yagi & Kokubu, 2019). The article refers to a publication by Christ and Burritt (2015) who argue that improvement measures are mainly case-based and too little research following comparative, quantitative approaches, e.g., between companies, exists. Consequently, MFCA research that focuses on the effects of MFCA is required (Yagi & Kokubu, 2018). This goes hand in hand with the goal of this dissertation, being the method's change of focus away from the evaluation of losses towards the evaluation of potential improvement measures. Once these measures have been identified, they can be evaluated with the method of MFCA (cf. Subsection 4.3.4).

In order to find suitable measures that reduce the losses identified and quantified with MFCA, case studies have tried out various pathways. These include design of experiments (DOE) concepts, the fishbone technique, Pareto and what-if analyses, field interviews, interviews with practitioners and experts, and the method of a scientific literature research (Chompu-inwai et al., 2015; Dunuwila et al., 2018; May & Günther, 2020; Tailor et al., 2017). Moreover, the analysis of the product supply chain and potential collaborations with business partners can be useful, as Japanese case studies suggest (METI, 2011; Nakano & Hirao, 2011). Additionally, the norm *VDI 4800 Part 1 Resource Efficiency—Methodological Principles and Strategies* (VDI, 2016) offers 37 strategies and measures for an increase in resource efficiency including practical examples. Two examples are *22 Avoidance of losses due to rework* and *33 Cascading use of auxiliary materials and operating supplies* (VDI, 2016, pp. 49, 51). Table 3 includes the 37 resource efficiency strategies and additional information on each of them such as whether they are related to the product or the production and which corporate departments are involved. The norm also contains information regarding measures and tangible examples. In conclusion, the norm offers valuable food for thought and can be consulted in the search for measures.

Table 3: Strategies for increasing resource efficiency—overview (Adapted from VDI, 2016, p. 39)

		Related to			Influential parties in the company				
No.	Strategy	Product	Production	Product development	Factory planning	Operations planning	Purchasing/ procurement	Production	Sales
1	Material choice/material substitution	X		X					
2	Lightweight design	X		X					
3	Mission match and safety	X		X					
4	Miniaturization	X		X					
5	Production-oriented product design	X		X		X		X	
6	Use-oriented product design	X		X					
7	Extension of technical lifetime	X		X					
8	Extension of product service life	X		X					
9	Product service systems (dematerialization)	X		X					
10	Cascading use of products	X		X					
11	Reparability	X		X					
12	Recycling-oriented product design	X		X					
13	Adding instructions on user behavior to the manual	X		X					
14	Resource-efficient packaging design	X		X				X	X
15	Manufacturing process selection and optimization		X		X	X		X	
16	Equipment dimensioning		X		X				
17	Minimization of machining volume		X	X	X	X		X	
18	Substitution of auxiliary materials and operating supplies		X				X	X	
19	Dry machining and minimum quantity lubrication		X		X			X	
20	Minimization of planned loss		X	X		X		X	
21	Minimization of planned scrap		X			X			X
22	Avoidance of losses due to rework		X	X				X	
23	Avoidance of losses due to disposal of finished products		X					X	X
24	Avoidance of losses due to disposal of purchased materials		X				X	X	
25	Avoidance of losses due to improper storage or obsolescence		X				X	X	
26	Reduction of energy consumption		X		X			X	
27	Efficient energy supply		X		X				
28	Use of process heat and waste heat		X		X			X	
29	Efficient building infrastructure		X		X			X	
30	Efficient building envelope		X		X			X	
31	Efficient cleaning		X		X			X	
32	Manufacturing-process-related recirculation		X		X			X	
33	Cascading use of auxiliary materials and operating supplies								
34	Efficient transport		X		X		X	X	X
35	Complete and unambiguous product documentation		X		X	X		X	
36	Detailed tasks descriptions and structured shift handovers		X		X	X		X	
37	Employee qualification/employee potential		X					X	

Second, the standard only mentions the term “saving potentials” (ISO, 2011, pp. 81, 85) in the Annex C twice. In practice, saving potentials are of great importance because they are a key figure to support management decisions. The norm assigns a value (e.g., monetary or environmental emissions) to the waste flows in the system under analysis, respectively. This value is correct if the flows follow linear relationships, respectively, *and* if all loss-containing flows in the system are eliminated to 100%. The value is also correct if the flows follow linear relationships, respectively, *and* if the loss-containing flow appearing first in the system under analysis in the direction of the material flow is eliminated to 100%. This also covers the case that the system under analysis comprises only one loss flow. The algorithms of MFCA following ISO 14051 do not enable the correct calculation of saving potentials for the cases which are included in the right column in Table 4. Only the cases in the left column of the table have been covered with the ISO 14051. Therefore, the extension of the method regarding the quantification of saving potentials represents a meaningful improvement.

Table 4: Cases for which MFCA 1.0 and MFCA 2.0 calculate the correct saving potentials

MFCA 1.0 (following ISO 14051)	MFCA 2.0
If the production system under analysis follows linear relationships and… - has exactly *one* loss flow and this loss can be saved - has multiple loss flows and *all* can be saved - has multiple loss flows and the loss flow *appearing first in the process chain* can be saved	If the production system under analysis… - has *multiple* loss flows and *less than all* and *not only the loss flow appearing first in the process chain* can be saved - follows non-linear mathematical relationships - contains a material loop

Unless these conditions are fulfilled, the MFCA results suggested in the norm are not able to deliver the desired information on the saving potentials, respectively. Besides the assumption of linear relationships between the different flows, these include cases in which the loss flow that can be reduced is not the first one appearing in the system following the direction of the material flow. Moreover, it is of high relevance for corporate practice to calculate the saving potentials that result from a partial reduction of losses, e.g., if a loss flow can be reduced by 40%. Therefore, in order to quantify the actual saving potentials, the systemwide changes of the flows in the system under analysis need to be determined and compared with the status quo of the model. Sygulla et al. (2011) have identified and expressed this need already. This approach reveals the actual saving potentials related to punctual improvements in the system under analysis. Since cost reduction is a major motivation for companies and their employees to apply the method of MFCA (Chompu-inwai et al., 2015; A. Schmidt et al., 2015; Sulong et al., 2015), it is a promising factor leading to an increase of the method’s popularity. Kokubu and Kitada (2015) also point out this aspect by emphasizing that the method is able to quantify the value of the material losses and that “[…] this information can be used for the evaluation of new equipment or the substituting of new raw materials in order to reduce losses” (Kokubu & Kitada, 2015, p. 1280). This thought goes beyond the ISO 14051 (ISO, 2011) because it focuses on measures such as new machines or alternative input materials. Section 4.2 addresses this shortcoming and describes the paradigm shift that is necessary to resolve it.

Third, as explained in Table 4, the MFCA approach based on the standard ISO 14051 is not able to deal with material loops in the system under analysis and hence, they are not mentioned in the standard. However, internal material recycling loops are of high relevance in corporate practice because it is a way to handle material losses internally and between companies, as the VDI (2016) suggests as one of the resource efficiency strategies. However, recirculation of material losses requires additional efforts such as energy, processing equipment and logistics. These efforts can only be quantified if they are included in the MFCA model. This, in turn, requires algorithms which are able to process material loops, i.e., that the output flow of one QC turns into an input flow of a preceding QC. This is a claim and one of the goals this dissertation pursues.

Fourth, MFCA can offer valuable information for companies on environmental emissions related to the material losses. Whenever applied in practice, MFCA should be paired with an environmental analysis of the process and the losses in particular. While MFCA's strength is certainly the combination of physical and monetary flows, the call of the progressing climate change crisis is to finally and permanently integrate the environmental dimension into the economic sphere. This has been suggested for MFCA years ago (M. Schmidt, 2015). The ISO 14051 does mention the environmental dimension of material losses, but it does not elaborate on its integration in the method and the quantification of environmental emissions when the method is applied. This represents a weakness in the stringency of the norm that can be eliminated with the full integration of the environmental dimension in the method.

Fifth, two aspects regarding the topic of allocation will be addressed. The ISO 14051 stipulates that the most appropriate allocation criteria should be determined by the organization implementing MFCA (ISO, 2011). Generally, the act of allocation is the foundation of every MFCA application. However, determining an allocation criterion can be challenging in a specific application because the criterion can be based on many parameters. The parameters can, for example, be weight, energy content, machine hours, labor hours or floor space, and they can be specified individually for the different kinds of costs, respectively (ISO, 2011). A challenging example represents cooling water, which is an indispensable in- and output in many production processes. While A. Schmidt et al. (2015) suggest using the intended output(s) as allocation criterion, thereby neglecting the evaluation of waste water as loss, M. Schmidt and Nakajima (2013) remark that waste water should not be neglected, particularly in countries with water shortages. At this point, the ISO standard is not specific enough and its appropriate implementation depends very much on the decision-maker(s) and their expertise.

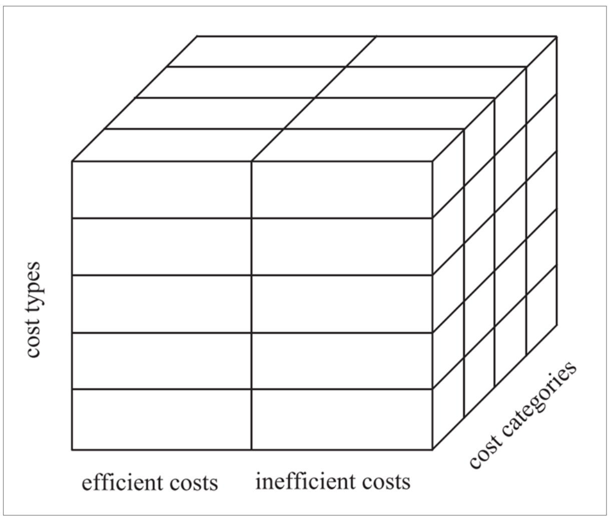
Moreover, allocation plays a role with regard to the analysis of a single product or a product group. Usually, an MFCA includes costs that accrue for products that are outside the scope of that specific MFCA analysis. Consequently, these cost factors need to be allocated between the different products for which they are relevant, and thus only part of the costs are included in the MFCA. However, this approach is an artificial breakdown and does not represent the actual situation because the costs accrue as a whole for a number of products which are oftentimes not congruent with the products in the focus of the MFCA. More than 90 years ago already, Camman (1932) pointed out that in the case of multiple products, the determination of the costs for one single product is impossible, but nevertheless, he argues that the isolation of a single product is a theoretical matter. There is another dissertation focusing on the MFCA method, and it conducted a written survey among authors of German cost accounting books (Walz, 2022). The survey revealed that first, some respondents find the fact that MFCA allocates costs between the product and the losses arbitrary. Second, the allocation can lead to misunderstandings and consequent wrong decisions because only product costs are considered (Walz, 2022). Without doubt, these risks should be recognized and reduced as much as possible.

Against this background, MFCA can be scrutinized in two respects. First, MFCA is grounded in the concept of allocation by differentiating product(s) from losses. Although allocation is an indispensable element, this work strives for a methodological advancement. Second, MFCA is often applied to a single product of a company or along a supply chain, thus oftentimes partitioning the efforts of joint production processes. In summary, allocation is at the heart of MFCA. In order to apply the method correctly and to understand and use the results in the correct way, it is essential to make transparent where allocation was conducted and what allocation criteria were applied. Moreover, an MFCA should make transparent what costs were included and what costs were not included in the analysis.

Sixth, the MFCA method lacks interdisciplinarity since it offers a purely technical approach. Since MFCA research has been mainly influenced by the engineering sciences, there is little room for interdisciplinarity (Kitada et al., 2022). However, a practice-focused analysis of the method explains the importance of interdisciplinarity for environmental management. The study also refers to Christ and Burritt (2015) who reviewed the MFCA method and concluded that there is a methodological gap between academic research focusing on technical and engineering aspects on the one hand and lacking use of the method in practice on the other hand. They identify a need for theoretical research that supports the further development and implementation of the method, such as the theory about diffusion of innovations in order to understand what encourages and what hinders the adoption of the method (Christ & Burritt, 2015; Rogers, 2003). The present research takes these findings into account, asks new research questions and thus offers new perspectives on the method. Through an interdisciplinary approach combining ecological, social and economic aspects, MFCA 2.0 is more practice-oriented. Additionally, it offers a new perspective for the evaluation of losses, and the accompanying consulting concept takes non-technical and qualitative aspects into account, including social implications when using the method.

Seventh, the MFCA method is not in line with cost accounting, which has a long history and tradition, especially in Germany. Cost accounting has been firmly established in practice and therefore, it obviously provides information for certain management needs. Dierkes and Siepelmeyer (2019) voice the lacking discussion of common cost types and unit cost accounting against the background of MFCA. They argue that MFCA should introduce so-called inefficiency factors and provide information on unit costs of the product(s) costs (Dierkes & Siepelmeyer, 2019). Figure 10 illustrates their MFCA system in the form of a cuboid, which comprises three dimensions, representing the dimensions of their MFCA system.

Figure 10: Cost types, cost efficiency, and cost categories as cost dimensions (Dierkes & Siepelmeyer, 2019, p. 489)



Moreover, they take up A. Schmidt et al.'s (2015) idea to use MFCA as marginal costing system in order to support short-term decisions (Dierkes & Siepelmeyer, 2019; A. Schmidt et al., 2015). *Kilger's Flexible Standard Costing and Contribution Margin Accounting* played an important role when Dierkes and Siepelmeyer (2019) developed their MFCA system. Riebel and his ideas on cost accounting do not appear in their work. With regard to the historical development of cost accounting, Kilger's work has had more influence on cost accounting practice than Riebel's work (see Section 2.6).

While conventional cost accounting allocates all inputs accruing in the system under analysis to the product, MFCA divides the input amounts to the products and the losses following certain allocation criteria (ISO, 2011). Since all costs are carried by the product, the costs of the losses and the corresponding saving potentials cannot be determined. Merely waste management costs, i.e., the costs that result from the management—oftentimes disposal—of the waste are captured separately and can therefore be associated with the occurrence of waste. Therefore, conventional cost accounting is unfamiliar with the cost carrier of losses, which may impede the implementation and integration of MFCA into existing cost accounting structures. Apart from the mentioned discrepancies with traditional cost accounting, MFCA is not in line with Riebel's cost accounting system. The identity principle, which is a central concept of the cost accounting system, only allows the allocation of costs to cost objects if they are both the result of the same decision (cf. Subsection 2.5.4, Riebel, 1994b). However, MFCA allocates costs to products and losses, which contradicts Riebel's approach (Viere et al., 2010). The existence of both product and loss is the result of the decision to manufacture the product. Conventional cost accounting is not familiar with the identity principle either, but the identity principle has the potential to adapt and improve the MFCA method so that it is aligned with conventional cost accounting. This may also make the implementation of the method in a corporate context easier. In summary, the history of cost accounting and its theoretical foundations allow interesting and promising paths for the improvement of the MFCA method and its compatibility with existing cost accounting practices. The work of the two German professors Riebel and Kilger and their academic discourse on accounting offers new insights and impulses regarding the MFCA method.

Due to these weaknesses, the incentive to pursue MFCA after an initial project to gain more transparency about the losses and the associated monetary and environmental losses remains small. Therefore, a methodological improvement of the method is necessary. It should focus on saving potentials and bring the method in line with conventional cost accounting. This leads to fundamental changes in the reasoning and the application of method, justifying the neologism *MFCA 2.0*. This will be implemented with a scenario-based approach, on which Chapter 4 is going to focus.

4 Rebirth of Material Flow Cost Accounting: MFCA 2.0

It is not more surprising to be born twice than once;
everything in nature is resurrection.—Voltaire

This chapter introduces and explains the new approach to the MFCA method titled *MFCA 2.0*. The MFCA approach described in the standard ISO 14051 (ISO, 2011) will be referred to as *MFCA 1.0* hereafter. Although the goal of the method to reduce material losses and to thereby increase resource efficiency stays the same, the shift of focus towards improvement potentials resembles a quantum leap, and it has the potential to advance the method's relevance for and implementation in corporate practice.

4.1 The Scenario-Based Approach

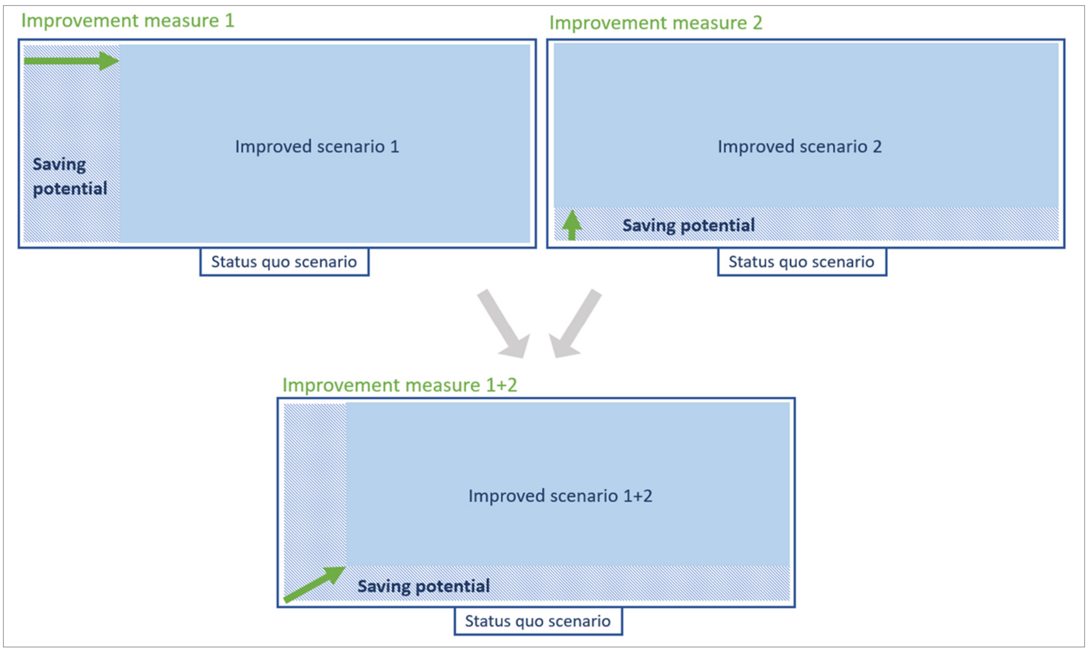
The scenario-based approach is a novel interpretation of the MFCA method because it is able to immediately quantify saving potentials. Andreas Möller—supervisor of this dissertation—had this idea in the first place so he shall receive due credit at the beginning of this section. Moreover, he has fathered the corresponding software application *Umberto 11*®, with which the Sankey diagrams in Section 4.3 were built. Unlike in the text elements of this work, the numbers in the Sankey diagrams use a comma as decimal separator, and no comma is used as thousands separator.

In order to calculate the saving potentials, the approach requires two states of an MFCA model under analysis. While one state represents the status quo of the system under analysis, i.e., the business-as-usual scenario, the other one represents an improved scenario, i.e., an improved state of the system that results from changes in the system. The changes can take on multiple forms such as different flow quantities, new input materials or changes in the process settings such as energy demands of certain QCs or machines. The analysis of a status quo scenario and an improved scenario is defined as *case* hereafter. The following calculations will focus on the reduction of material loss flows, which reflects the key idea of MFCA 2.0: The reduction of material losses in the system under analysis leads to an increase in resource efficiency. It is self-explanatory that an MFCA analysis requires at least one material loss flow in the status quo of the system to be analyzed. Once these two scenarios have been defined and calculated, the improved scenario gets subtracted from the business-as-usual scenario. The resulting difference can be expressed in physical units such as mass and energy, but also in monetary units or environmental emissions such as kg CO_2e. The monetary and emissions-based saving potentials require cost and emission factors, respectively, which are then multiplied with the physical units. This scenario-based approach is the core idea of MFCA 2.0, and it enables the accurate quantification of the improvement in terms of mass, energy demand, costs and emissions in a handy way.

Figure 11 illustrates the scenario-based approach of MFCA 2.0 in an abstract and simplified way. The figure is composed of three elements. The elements at the top left and at the top right include one improvement measure, respectively. These two improvement measures are then combined in the illustration below. Focusing now on one element, the area inside the dark blue framings in Figure 11 depict the amount of loss prevalent in the status quo scenario. The green arrows illustrate an improvement measure, respectively, i.e., the arrow at the top left represents improvement measure 1, and the arrow at the top right represents improvement measure 2. The element below combines the two measures, which are illustrated with the diagonal arrow.

This abstract, two-dimensional illustration demonstrates three aspects of the scenario-based approach. First, the green arrow illustrates the improvement measure, which reduces the amount of loss in the system under analysis. Consequently, the area of the improved scenario is smaller than the area of the status quo scenario. The scenario-based approach subtracts the improved scenario from the status quo scenario, thus determining the difference between these two scenarios. This area represents the saving potential, which is visualized with the hatched area. Second, the green arrow is one-dimensional. The saving potential is depicted as an area, i.e., it is two-dimensional. This explains that although the improvement measure may be implemented at one point in the system where it reduces a single loss flow, it leads to the reduction of other flows since the flows are related to each other, hence increasing the efficiency of the system as a whole. The quantification of this saving potential based on an improvement measure is the additional information MFCA 2.0 can deliver. Using the illustration of Figure 11, the area representing the saving potential cannot be determined with the information about the length of the arrow representing the improvement measure alone. The width of the area is required as well. In an analogous manner, the determination of the saving potential resulting from an improvement measure requires more information than just the amount of loss the measure can reduce. Third, the combination of improvement measures—which represents a case—does not mean that the corresponding saving potentials can simply be added. The effects of multiple improvement measures do not necessarily follow the summation principle. As can be seen in Figure 11, the area of the saving potential for the element below with improvement measures 1 and 2 is not the total amount of the saving potential areas of the upper two elements. The illustration of this aspect with different areas is an abstract depiction in order to visualize the effect. That means the area of the saving potential symbolizes the effect of one single improvement measure, while the overlapping area symbolizes the effect of two improvement measures implemented at the same time. Therefore, the saving potential needs to be determined case-specific, using the scenario-based approach.

Figure 11: Abstract illustration of scenario-based logic of MFCA 2.0 (Own illustration)



The scenario-based approach is also able to handle material loops. A material loop leads a material flow that used to be a material loss flow back into the system under analysis, thus forming a system-internal material loop. Although this avoids the occurrence of a material loss and its disposal on the one hand, the system-internal material loop also requires additional efforts such as energy and system costs on the other hand. Again, this weighing is ultimately a case-specific question that cannot be universally answered. Viere et al. (2010) and M. Schmidt (2012) have already described how the additional effort and corresponding saving potential of loops in the system under analysis can be determined. System-internal material loops are a common practice in industrial manufacturing processes and since they circumvent immediate material losses, they are an important object of investigation (M. Schmidt, 2012; Viere et al., 2010). In order to evaluate a measure that closes a material loop, the net effect is required, which can be precisely determined with the scenario-based approach of MFCA 2.0. It is able to quantify the saving potentials based on the values of the status quo of the system under analysis and the improved scenario including the measure with the material loop. Vice versa, MFCA 2.0 can review whether an existing material loop is worthwhile from a resource-based, economic and GHG emissions-based point of view and answer the question whether the operation of the system with the material loop really requires less effort than the scenario in which the material loop is broken, meaning that the material output flow is accepted as a loss flow. Once the effort that the material loop requires or reduces has been identified, the results can be used to evaluate and compare potential reduction measures including the related costs. Although recycling may seem a reasonable way of handling the material losses, avoiding the losses from the outset may be a more desirable alterative—despite the additional costs related to the reduction measures. The step-by-step procedure will be explained in Section 4.3 in more detail including a numerical example and a specific model. Therefore, MFCA is an important tool that questions the status quo including material loops and supports corporate decision-making with quantitative data, paving the way to more resource-efficient manufacturing processes.

4.2 The Paradigm Shift to MFCA 2.0

The shift of focus away from the evaluation of the losses towards the evaluation of improvement measures and the corresponding saving potentials represents a paradigm shift for the method of MFCA. While the ISO standard—representing MFCA 1.0—focuses on the question *How much is being wasted because of the losses?*, MFCA 2.0 strives to answer the question *How much can be saved if we manage to reduce the losses?*. This is a practice-oriented improvement of the method because it enables the accurate evaluation of different action alternatives in the form of saving potentials, which has not been part of the method until now. While MFCA 1.0 evaluates material losses, MFCA 2.0 evaluates the effect of measures in the form of specific changes in the analyzed system. First, the measure has direct effects at the point in the system where it is located, i.e., the quantity center in the model. Second, there are indirect effects on other processes and the corresponding flows in the system under analysis that lie outside the scope of MFCA 1.0. Therefore, MFCA 2.0, with its scenario-based approach, offers a methodological extension.

This paradigm shift was also inspired by Rummel's article from 1936 in which he writes about the materials industry. He argues how important it is to critically analyze balance sheets, i.e., inputs and outputs (Rummel, 1936). The following direct quote describes this line of argument. It shall emphasize the method's strength and support the illustration of the paradigm shift.

> All important influencing factors are identified and with the help of special tools, the impacts of these influencing factors will be worked out and systematized. Thinking in balances makes the sources of losses clearer, the calculation with carefully evaluated quantities helps choosing the right material, the most useful process, the right machine. (Rummel, 1936, p. 228, own translation from German)

The evaluation of improvement measures is decision-oriented as it provides management with data for different action alternatives, thus supporting corporate decision-making. The data comprises saving potentials in physical, monetary and environmental units for different improvement options. Depending on the context and the corporate goals, one or two of the dimensions can be prioritized, or all three can be considered equally in decision-making. For example, a company can set the goal to reduce its resource dependence. Consequently, the focus will lie on the reduction of material and energy demand, i.e., in physical units, through the material loss reduction. Cost reduction can also be chosen as the primary objective in an MFCA, which shifts the focus to monetary values and cost reduction potentials. A third goal can be the reduction of environmental emissions. In this case, GHG emissions saving potentials need to be quantified with the help of the relevant emission factors and the scenario-based approach of MFCA 2.0. The method is now able to provide active and data-based decision support for specific operational issues.

Moreover, corporate goals can combine different dimensions, and they can be pursued with the help of MFCA 2.0. For example, a corporate goal may be climate neutrality, i.e., the combination of the minimization of corporate GHG emissions and compensation activities. In this application example, MFCA 2.0 can be used to reduce corporate GHG emissions. With the evaluation of different action alternatives, the GHG emissions saving potentials as well as the monetary costs or benefits of a reduction of material losses can be specified with MFCA 2.0. The quantification of the saving potentials as a decision criterion is of prime importance with regard to the plethora of key performance indicators such as the return on investment (ROI) of a measure or the overall equipment effectiveness (OEE) of a production process. Although they are definitely informative for certain management decisions, they do not address the topic of resource efficiency in the way in which MFCA 2.0 does because they focus on different aspects of the system. Furthermore, MFCA 2.0 results can be used in addition to traditional decision criteria, thereby gradually shifting the focus from rather profit-driven- and short-term-oriented decision criteria towards more holistic decision criteria including resource-related and environmental aspects.

Riebel's identity principle (see Subsection 2.5.4) regards a decision the true cause of a cost incurrence (Riebel, 1994b). Moreover, the identity principle connects decisions with measures because measures are a necessary and inevitable consequence on the process level, such as a procurement or a payment order (Riebel, 1994b). This logic has now been applied to the method of MFCA, providing the basis for MFCA 2.0. Against this background, a decision includes the reduction of material losses in the system under analysis, which requires a specific measure that changes the system. The scenario-based approach reflects this line of thought because it quantifies the difference between the system without the measure or package of measures (status quo) and the system with the measure or package of measures (improved scenario). It answers the question of how and to what extent a specific decision affects the system under analysis. MFCA 2.0 embraces the identity principle, which allows the allocation of costs to cost objects only if they were both caused by the same decision (Riebel, 1994b). The application of the identity principle to the method of MFCA requires another change of the method regarding the monetary viewpoint and model. Since the decision to produce a predefined amount of one product or of several products never aims at the production of losses in the first place, all costs (and GHG emissions) should be carried by the product(s). The allocation of the production costs to the product(s) brings MFCA in line with conventional cost accounting. Cost accounting exists in any commercial enterprise, and the convergence with MFCA 2.0 will thus support the method's practicability and implementation.

4.3 The New Algorithm of MFCA 2.0

The algorithm of MFCA 2.0 is the focus of this section. It can be applied to linear and non-linear process conditions. To show this, different application examples will be used and presented. The explanations will be supported with illustrations created with the software application *Umberto 11®* by iPoint-systems GmbH (n.d.). *Umberto 11®* is an exemplary implementation of the algorithm and it supports the understanding of the approach of MFCA 2.0. Nevertheless, the method can also be applied without the software. Generally, MFCA can be applied with any calculation software such as Excel®, and also with pen and paper.

4.3.1 Mathematical Relationships in MFCA 2.0

In general, MFCA allows different ways to model relationships an MFCA model such as material quantities, energy quantities or costs. This subsection will give an overview of the possibilities with some specific examples. The first option are linear specifications with the options of parameterizing them and using fixed values. For example, input flows such as wages or maintenance costs can be parameterized and quantified as follows:

p = number of product units produced in a given time period, e.g., per month

- Wage costs = 3,500 EUR + 2.00 EUR/product unit · p
- Maintenance costs = 1,000 EUR + 0.002/product unit · p

Another example and special case for a linear specification are rental costs, which are usually constant over a certain period of time such as a month, and they do not depend on the number of product units, as the following example shows:

- Rental costs = 5,000 EUR

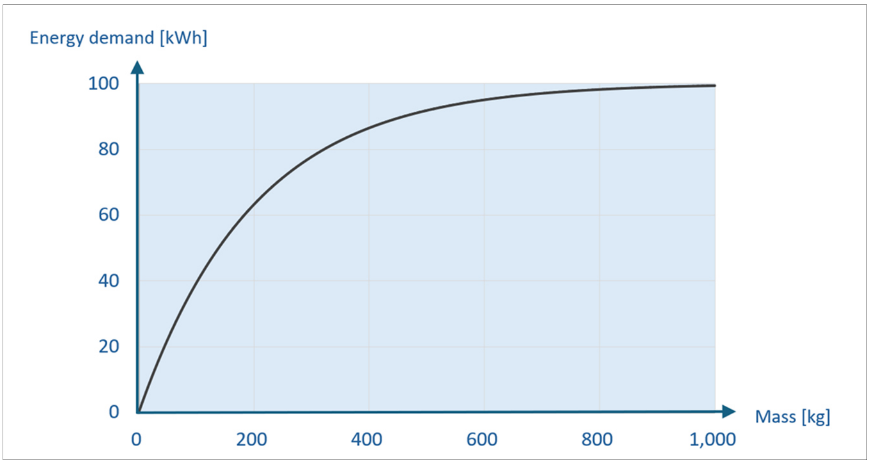
The second option comprises another sort of user-defined functions, i.e., functions that can be defined with mathematical non-linear equations. This is relevant and helpful for processes or cost functions whose output values do not depend on the input values in a linear way. An example is the energy demand in a heating process, which may increase with the mass of the input material in the following non-linear way:

m: mass of the material input flow in the QC

- Energy demand = 100 kWh – 100 kWh · $e^{-0.005 \cdot m/\text{kg}}$

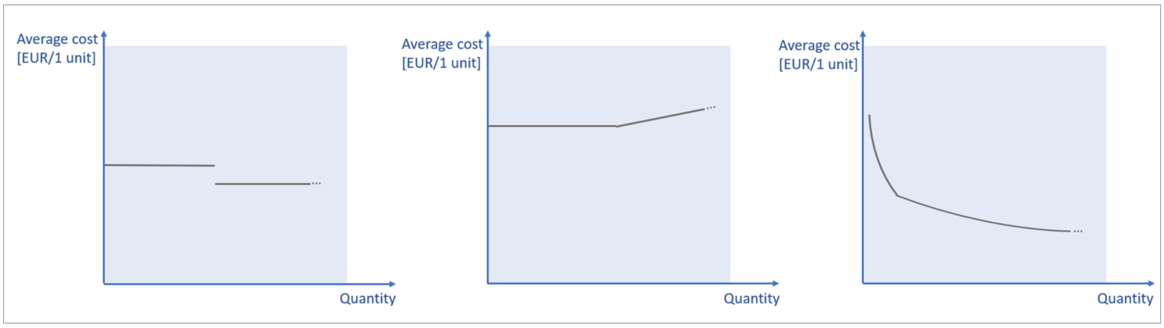
Figure 12 shows a graphical illustration of the described energy demand function. The example shows an exponential growth function whose energy demand is dependent from the input mass. Energy demand converges to the asymptote of 100 kWh.

Figure 12: Exemplary energy demand as a function of mass (Own illustration)



The different functions offer a plethora of possibilities to define the relationship between two quantities. They comprise basically any mathematical function such as quadratic or exponential functions, jump functions, and operations such as average, median, minimum or maximum. Riebel (1994b) supports non-linear mathematical relationships against the background of his cost accounting approach as he argues that marginal costs cannot be defined via average values or linear functions. He gives several examples like bulk prices, the renumeration of overtime as personnel costs or electricity prices that follow multilayered terms and pricing systems. The following Figure 13 contains three examples of non-linear cost functions. The average cost (y-axis) is shown depending on the quantity (x-axis), and in the three examples, the average cost develops in different ways. The example on the left depicts bulk prices as the average price reduces with a certain value on the x-axis, i.e., a certain quantity. The diagram in the middle shows the concept of salary costs with the renumeration of overtime if the hours worked exceed the amount contracted. The average costs remain constant to a certain value, and they constantly increase from that value on. Finally, the diagram on the right illustrates a pricing system for electricity. While there is a basic fare independent from the amount of electricity consumed, there are different unit prices depending on the total amount of electricity consumed, leading to decreasing average costs. These exemplary illustrations explain why costs can only be averaged within certain limits. In any case, the underlying assumptions should be explicitly stated in order to increase transparency and to handle the costs correctly.

Figure 13: Three examples of non-linear average cost functions (Adapted from Riebel, 1994b, pp. 416f.)



In summary, the illustrated mathematical functions enable a more manifold application of the MFCA 2.0 method as they allow the precise depiction of the relationship between different quantities such as materials, energy and costs in linear and non-linear mathematical functions. In combination with the new algorithms, MFCA 2.0 is more practice-oriented and allows its users to depict the production reality in the model more accurately. This is an important prerequisite for the quantification and comparison of improvement measures regarding their improvement potential. In the following, linear (Subsections 4.3.3, 4.3.4, and 4.3.5) and non-linear (Subsection 4.3.6) examples will be explained. Since the focus of this chapter lies on the description and illustration of the MFCA 2.0 algorithms, a description of the background of the application example including specific technologies will not be included.

4.3.2 Linearity in MFCA

Having introduced different mathematical functions, the topic of linearity will be examined more closely in this subsection. Although *linearity* as term cannot be found in the standard ISO 14051 (ISO, 2011), the allocation of energy and system costs is done "by using an appropriate apportionment basis" (ISO, 2011, p. 11), which appears to be linear in all calculation examples of the standard. Therefore, the topic of linearity will be discussed in the following.

First of all, MFCA is an environmental management accounting method that pursues the goal to depict reality in a model. This usually requires some simplifications, which in turn lead to a certain degree of inaccuracy. However, this does not mean that the model is incorrect or useless. This would be a logical fallacy because without simplifications such as mathematical functions, an MFCA model could not be created in the first place. Reality is oftentimes multilayered and relationships are complex, requiring a certain degree of simplification.

Second, linearity as an assumption can be a reasonable first step in an MFCA analysis. Linear and non-linear assumptions alike can be inappropriate assumptions with regard to the following analysis. In fact, there are linear relationships such as electricity consumption of lighting systems in dependence on its operating hours. As the project proceeds and progresses, mathematical relationships can be refined or redefined.

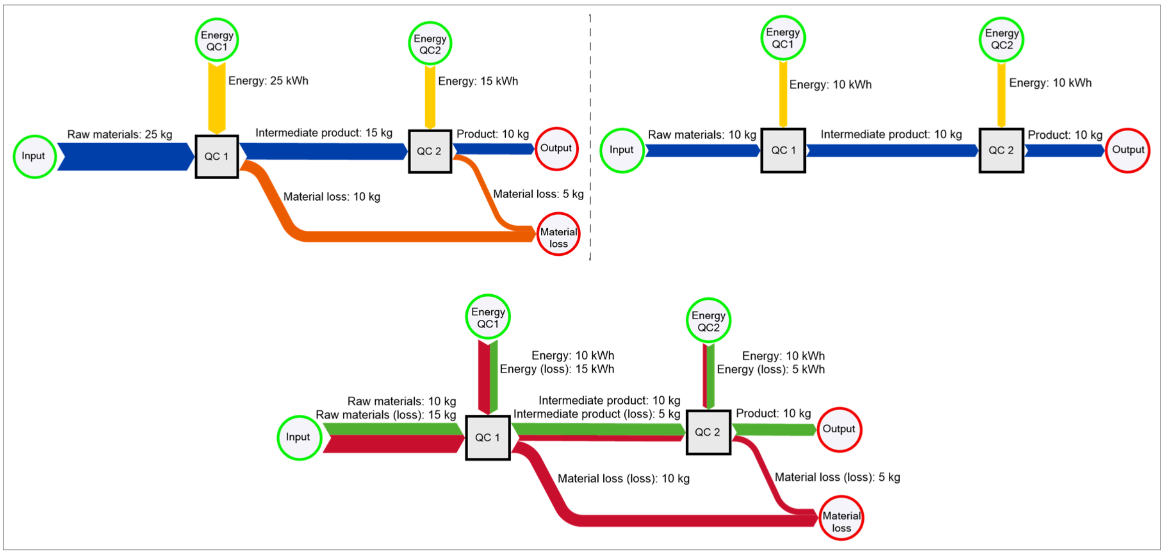
Third, the new algorithm of MFCA 2.0 using a scenario-based approach reframes the purpose of MFCA. Instead of focusing on material losses alone, it strives to quantify saving potentials as a result of material loss reductions. This increases the method's degree of freedom from a mathematical perspective.

In summary, linear mathematical relationships can be a good starting point, but linearity is not a must in MFCA. Generally, the definition of mathematical relationships should always take place in close cooperation with the respective company representatives, process owners and technical specialists. The scenario-based approach of MFCA 2.0 makes the method more flexible and allows the calculation of different saving potentials. The model can comprise different mathematical functions including linear and non-linear relationships. Therefore, linearity is not a prerequisite nor an assumption of an MFCA model or analysis.

4.3.3 The New Algorithm of MFCA 2.0: Physical, Monetary, and Emissions-Based Dimension

The physical dimension of an exemplary MFCA model consisting of two quantity centers is shown in Figure 14 with three Sankey diagrams. The diagram at the top left shows the status quo of the material and energy flows including the loss flows as the result of the production processes of the two quantity centers, respectively. In the status quo, the specific consumption rates of the inputs required for the process such as energy, work time or machining time are determined. In these processes, linear relationships are assumed. Per kg material, 1 kWh energy is required in each QC. The diagram at the top right shows an ideal scenario without any loss flows. Consequently, the input and intermediate flows are reduced in a linear way, which is why these flows are narrower in size. However, the product amount and hence the product flow remain unchanged. The elimination of all loss flows to 100% is obviously an ideal scenario, but it is used at this point to quantify the theoretical maximum saving potential and to show the range of possible savings in between. The Sankey diagram below the upper two diagrams represents the result of the new approach. In comparison to the two diagrams above, this one includes the colors green and red only. This color coding combines the status quo scenario and the improved scenario without the losses. The input flows are divided into the colors green and red: The product flow is colored in green only and the loss flows are colored in red only. The green shares show the flows as a result of the improved scenario. The red shares are the difference between the two scenarios, i.e., the red shares represent the saving potential for the analyzed system under the condition that the production volume stays constant. In the example, this means that if the material losses of 10 kg (QC1) and 5 kg (QC2) can be eliminated, the production of 10 kg requires 20 kWh in total. Consequently, the material-based saving potential is 60% and the energy-based saving potential is 50%. This means that if the loss flows are eliminated, the system under analysis can be streamlined, flows can be reduced and as a result, its material and energy efficiency, i.e., the system’s resource efficiency, will be improved.

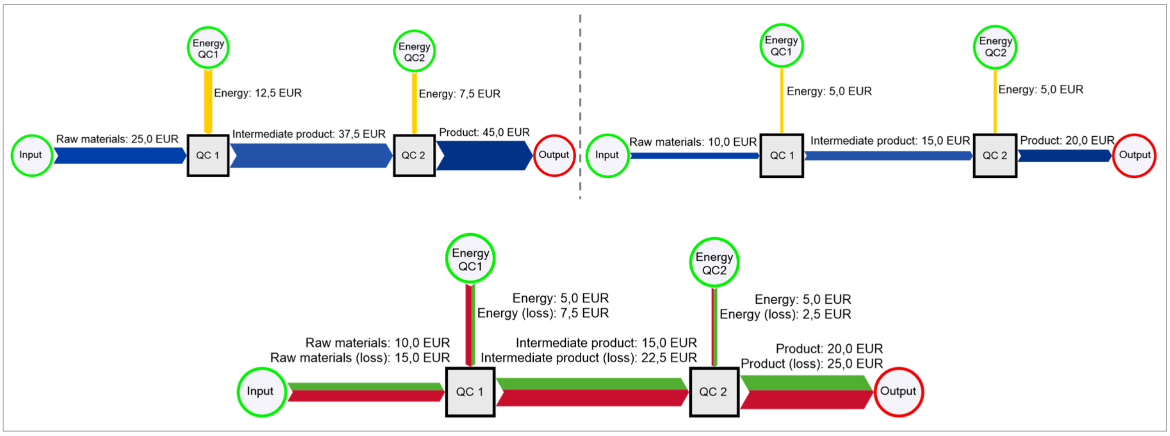
Figure 14: Sankey diagrams showing the status quo (top left), the improved scenario (top right) and the MFCA 2.0 diagram (bottom)—physical flows



Note: The diagram at the bottom of the figure results from the differences of the two scenarios. The red shares illustrate the saving potentials. Linear relationships are assumed.

The monetary dimension of the exemplary MFCA model is illustrated in Figure 15. To define this model, purchase prices and other costs need to be specified for the input flows, respectively. In the example, the price for raw materials is 1.0 EUR/kg and for energy 0.5 EUR/kWh. To keep the model simple, waste management costs are assumed to be 0.0 EUR/kg. What is eye-catching for the MFCA-trained eye is that the losses do not flow into a separate output place anymore. This is a result of the alignment of the method with traditional cost accounting practice and the implementation of Riebel's identity principle. The monetary dimension of MFCA 2.0 does not differentiate between product and loss in the same way MFCA 1.0 does. All costs are allocated to the product or product bundle. In Riebel's wording, this means that all costs are the result of the corporate decision to manufacture the product in the first place, which is why they are allocated to the product. In the analysis of "Material Flow Cost Accounting in the Light of the Traditional Cost Accounting [sic]" (Günther, Rieckhof, et al., 2017), the authors also suggest that "the entire costs of both product and non-product are assignable to the product" (p. 11). This has now been implemented with MFCA 2.0. All flows in the model end up in the final product flow, adding up to 45.0 EUR in the example (model at the top left in Figure 15). In addition to the alignment with traditional cost accounting, MFCA 2.0 adds a new perspective to the method, which builds on the scenario-based approach. The decision to manufacture the product can be combined with the decision to eliminate the material losses in the system under analysis. The resulting cost reduction can be quantified with the deduction of the amount of costs of the improved scenario without material losses from the amount of costs of the status quo scenario. In the example, the amounts are 45.0 EUR and 20.0 EUR, respectively. The difference of 25.0 EUR—55.6% of the total cost—represents the saving potential and it is illustrated with the red share of the product flow in the model below in the middle of Figure 15. As the red shares of the input flows show, the saving potential grows over the course of the production process. MFCA 2.0 is in line with Riebel's identity principle because the measure that changes the system under analysis and eliminates the material losses can now be evaluated with a specific cost reduction potential, thereby combining the two dimensions resource efficiency and cost efficiency.

Figure 15: Sankey diagrams showing the status quo (top left), the improved scenario (top right) and the MFCA 2.0 diagram (bottom)—monetary flows



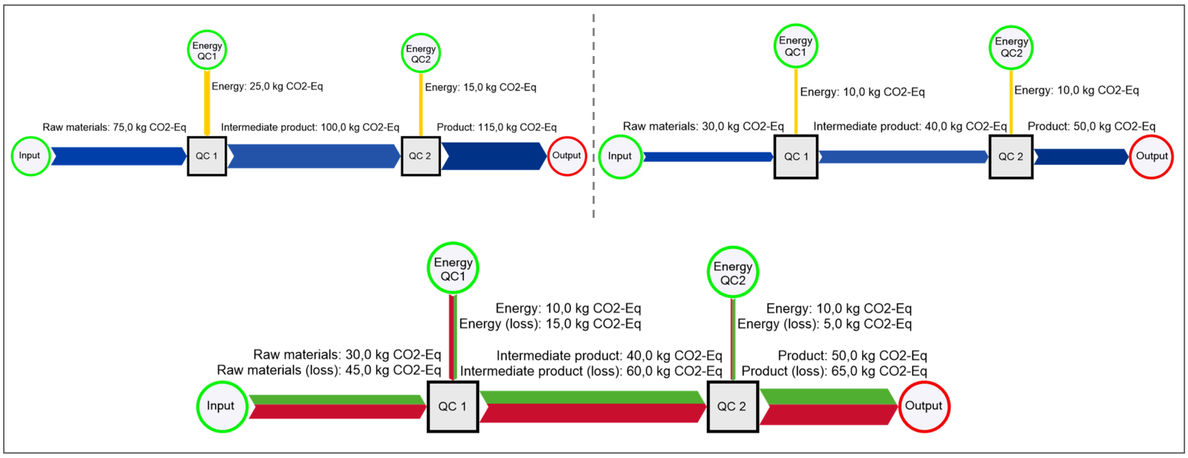
Note. The diagram at the bottom of the figure results from the differences of the two scenarios. The red shares of the flows illustrate the saving potentials. Constant prices per unit are assumed.

The scenario-based algorithms of MFCA 2.0 comprise an emissions-based dimension as well. Emission factors can be added to the model with the help of the approach described by M. Schmidt (2015), which uses emission factors to calculate the emissions of the different flows. With the help of emission factors, the environmental dimension can be added to the MFCA model. There are various environmental databases such as Probas by the Federal Environment Agency of Germany (Umweltbundesamt, UBA) (n.d.), Ecoinvent (2022) or Gabi (Sphera Solutions GmbH, n.d.). Moreover, the European Commission proposed a potential framework for an environmental footprint database including its development and maintenance (European Commission, Directorate-General for Research and Innovation, 2025).

This work focuses on GHG emissions in kilogram carbon dioxide equivalents (kg CO_2e) because the impact category climate change measured in kg CO_2e is important and much discussed these days. Moreover, the focus on CO_2e limits the length of the following descriptions. However, depending on the availability of data regarding other emissions, any other environmental emission unit such as SO_2e for acidification potential can be inserted and analyzed with the method.

Figure 16 shows the Sankey diagrams for the exemplary model. The emission factor for raw materials is assumed to be 3.0 kg CO_2e/kg and 1.0 kg CO_2e/kWh. Like in the Sankey diagrams for the monetary dimension, all emissions are allocated to the product. This is also rooted in Riebel's identity principle. MFCA 2.0 brings the environmental dimension of the method in line with traditional cost accounting by allocating all emissions to the product. Based on this logic, the element at the top left in Figure 16 shows the status quo, while the one in the middle shows the ideal scenario in which all material losses are eliminated. The model at the top right shows the resulting MFCA 2.0 approach. The red shares are related to the material losses, and they are calculated with the scenario-based approach by deducing the improved scenario from the status quo model at the top left. The emissions-related saving potentials are then plotted in the form of the red shares of the flows in the model at the top right. While each input flow has its specific saving potential, the saving potentials accumulate along the process, and their total amount can be read off the product flow. In the example, 65.0 kg CO_2e can be saved in total. It is the sum of 15.0 kg CO_2e and 5.0 kg CO_2e due to reductions in energy demand, and 45.0 kg CO_2e stemming from raw material reductions due to the efficiency increase. This represents a GHG-based saving potential of 56.5%. In conclusion, an efficiency increase of the system through the implementation of a loss-reducing measure can now be evaluated from an environmental perspective, thereby providing relevant information for corporate decision-makers pursuing environmental goals.

Figure 16: Sankey diagrams showing the status quo (top left), the improved scenario (top right) and the MFCA 2.0 diagram (bottom)—GHG emissions-based flows



Note. The diagram at the bottom of the figure results from the differences of the two scenarios The red shares illustrate the saving potentials. Constant GHG emissions per unit are assumed.

4.3.4 A Specific Example of an MFCA Model With Three Quantity Centers

In this subsection, MFCA 2.0 will be depicted with a specific example. After the introduction of the MFCA model in Paragraph 4.3.4.1, the new algorithms—enabling the quantification of saving potentials—will be explained with calculations, text, Sankey diagrams and tables in the following paragraphs. The following equations and calculations assume that the relationships between the flows are all linear. This means that all material inputs are homogeneously mixed in the respective quantity center, thus generating the intermediate products and the final product. However, as Subsection 4.3.1 already pointed out, the scenario-based approach does not require linear relationships. The algorithm will be illustrated with a non-linear example in Subsection 4.3.6.

4.3.4.1 Introduction: An MFCA Model With Three Quantity Centers Based on MFCA 1.0

The exemplary model comprises three quantity centers (QCs) and it refers to a one-month period. Each QC requires material and energy inputs, and system costs accrue as well. These three input flows are visible in the three QCs, respectively. Additionally, material losses occur in each of the three quantity centers. The materials A, C and E are homogeneously mixed in the respective QC, thus forming the intermediate products and the final product. The designations *Material A*, *Material C* and *Material E* are aligned with the general flow designation in Figure 20 in Paragraph 4.3.4.2, which is the basis for the derivation of the equations for the calculation of the saving potentials. The flows are measured in the following units:

- Raw materials [kg]
- Energy [kWh]
- System costs [EUR]

Energy demand and system costs are linearly dependent from the mass of the material input of the QC. Energy demand and systems costs can be calculated with the following factors in Table 5.

Table 5: QC-specific factors for energy demand and system costs per kg input material

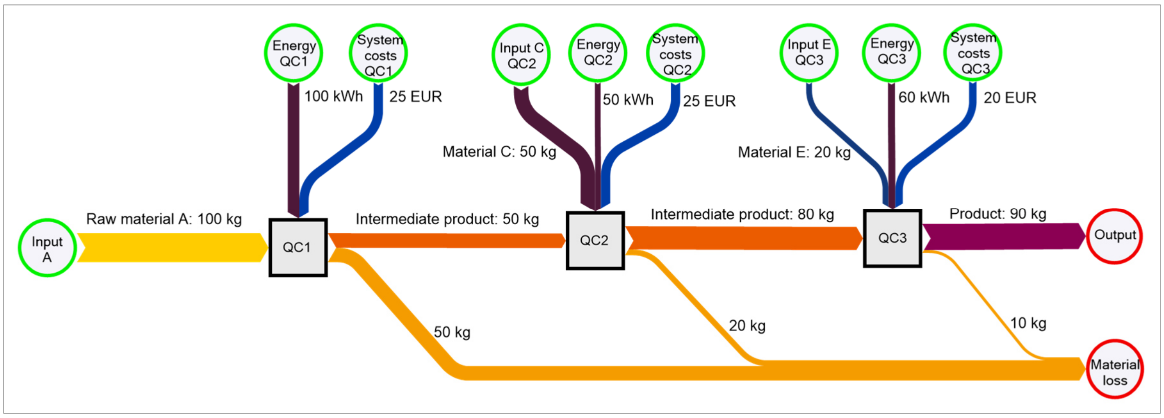
	QC1	QC2	QC3
Energy demand	1.00 kWh/kg	0.50 kWh/kg	0.60 kWh/kg
System costs	0.25 EUR/kg	0.25 EUR/kg	0.20 EUR/kg

The following Table 6 contains the MFCA results for the physical dimension based on the ISO 14051 (ISO, 2011). The following tables containing the MFCA data and results will follow certain rules: First, to use the number of decimal places sparingly, decimal places will only be stated if they are significant. Second, the maximum number of decimal places is two, i.e., the value will be rounded to the second decimal place. Third, all table values within one column will have the same number of decimal places (exceptions occur in Subsection 4.3.6 if the column is divided by a horizontal line). Summands specified in a table field only contain one decimal number, if significant. Figure 17 shows the corresponding Sankey diagram. In the Sankey diagrams, the same rules apply, but the third rule applies to all the values given in the Sankey diagram, i.e., the number of decimal places is the same for all values in the Sankey diagram.

Table 6: MFCA matrix, physical values

MFCA matrix	QC 1			QC 2			QC 3		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Inputs from previous QC				50	50	12.5	80	80	30
New inputs in QC	100	100	25.0	50	50	25.0	20	60	20
Total in each QC	100	100	25.0	100	100	37.5	100	140	50
Product of QC	50	50	12.5	80	80	30.0	90	126	45
Material losses (following ISO 14051:2011)	50	50	12.5	20	20	7.5	10	14	5
Total losses	50	50	12.5	70	70	20.0	80	84	25
Total amounts in the product of this process (all QCs)	90	126	45.0						

Figure 17: Sankey diagram of the MFCA model, status quo—physical flows



In summary, 80 kg of material losses accrue along the process chain to produce 90 kg product. Based on these numbers, the resulting loss rate is 0.89 kg/kg product[28] and 0.47 kg/kg input material[29]. The material efficiency rate of the process chain under analysis is 53%[30], and the energy efficiency rate is 60%[31] (based on the material flows). The total energy demand is 2.33 kWh/kg product[32].

In order to quantify the monetary flows, the following prices are added to all input flows:

- Raw material A: 1.00 EUR/kg
- Raw material C: 1.50 EUR/kg
- Raw material E: 2.00 EUR/kg
- Energy: 0.50 EUR/kWh
- Waste management costs: 1.00 EUR/kg

Table 7 includes the monetary values for the MFCA results following the standard ISO 14051 (ISO, 2011). The total cost of the status quo is 470 EUR.

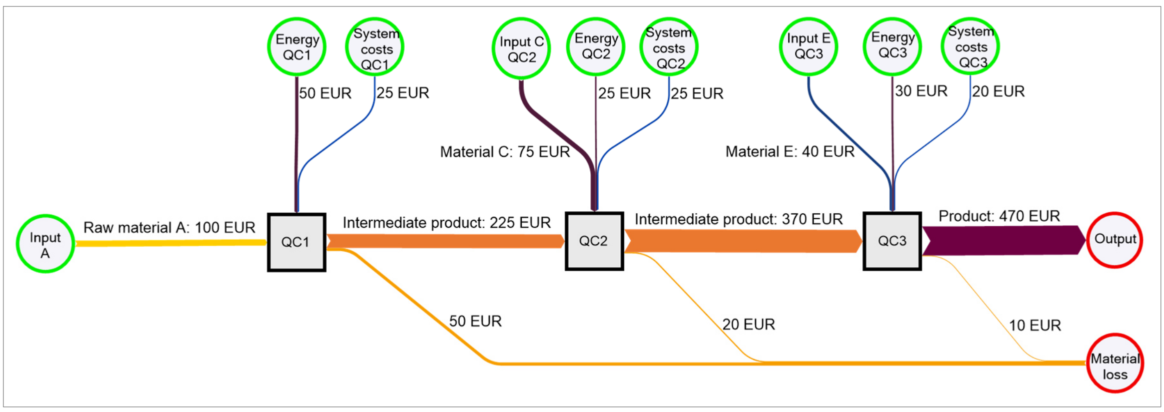
[28] (50 kg+20 kg+10 kg)/90 kg = 0.89 kg/kg product
[29] (50 kg+20 kg+10 kg)/(100 kg+50 kg+20 kg) = 0.47 kg/kg input material
[30] 90 kg/(100 kg+50 kg+20 kg) = 53%
[31] ((100 kWh·50 kg/100 kg+50 kWh)·80 kg/(50 kg+50 kg)+60 kWh)·90 kg/(80 kg+20 kg)/(100 kWh+50 kWh+60 kWh) = 60%
[32] (100 kWh+50 kWh+60 kWh)/90 kg = 2.33 kWh/kg

Table 7: MFCA matrix, monetary values

MFCA matrix	QC1				QC2				QC3			
	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs
	EUR	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*
Inputs from previous QC					50	25	12.5		100	40	30	
New inputs in QC	100	50	25.0		75	25	25.0		40	30	20	
Total in each QC	100	50	25.0		125	50	37.5		140	70	50	
Product of QC	50	25	12.5		100	40	30.0		126	63	45	
Losses (following ISO 14051:2011)	50	25	12.5	50	25	10	7.5	20	14	7	5	10
Total losses	50	25	12.5	50	75	35	20.0	70	89	42	25	80
Total amounts in the product of this process (all QCs)	126	63	45.0									
Total costs in this process (all QCs) status quo	100+75+40 =215	50+25+30 =105	25+25+20 =70.0	50+20+10 =80								
Total costs, status quo (all QCs)	470											

Figure 18 includes the Sankey diagram with the monetary flows. All costs flow in the direction of the product since all costs are to be carried by the product. This includes waste management costs, which is why the costs related to waste management flow towards the quantity centers and then towards and finally into the product flow, respectively.

Figure 18: Sankey diagram of the MFCA model, status quo—monetary flows



For the emissions-based dimension, GHG emission factors have been added to the model. Following the logic of the cost dimension, the emissions related to the management of the material losses are allocated to the product as well, which is why the flow direction is the opposite direction compared to the physical flows, i.e., from the material loss towards the product. The following GHG factors have the same values as the cost factors.

- Raw material A: 1.0 kg CO_2e/kg
- Raw material C: 1.5 kg CO_2e/kg
- Raw material E: 2.0 kg CO_2e/kg
- Energy: 0.5 kg CO_2e/kWh
- System environment: 1.0 kg CO_2e/EUR
- Waste management: 1.0 kg CO_2e/kg

This is obviously not an accurate depiction of reality, but these values were chosen to show that the calculations of GHG emissions follow the same logic and algorithms as the cost calculations. This aspect will be demonstrated with the following application examples and the corresponding cases. The example shall explain to manufacturing companies that the concept of GHG emissions is not difficult to comprehend, which can be a reason why companies are hesitant to address this topic proactively. However, with the help of MFCA 2.0, the topic can be made tangible: Emission factors can be used to calculate GHG emissions in the same way as costs can be quantified with cost factors such as purchase prices. This reduces inhibitions due to methodological insecurities.

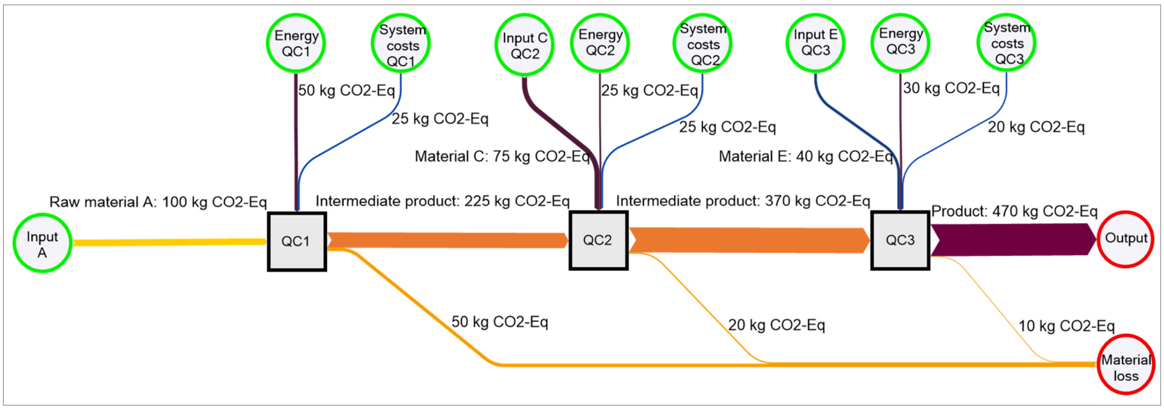
Table 8 includes the figures representing the GHG emissions-based dimension. The total GHG emissions amount to 470 kg CO_2e, as shown in the bottom row.

Table 8: MFCA matrix including MFCA 2.0, GHG emissions

MFCA matrix	QC1				QC2				QC3			
	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt
	kg CO_2e	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*
Inputs from previous QC					50	25	12.5		100	40	30	
New inputs in QC	100	50	25.0		75	25	25.0		40	30	20	
Total in each QC	100	50	25.0		125	50	37.5		140	70	50	
Product of QC	50	25	12.5		100	40	30.0		126	63	45	
Losses (following ISO 14051:2011)	50	25	12.5	50	25	10	7.5	20	14	7	5	10
Total losses	50	25	12.5	50	75	35	20.0	70	89	42	25	80
Total amounts in the product of this process (all QCs)	126	63	45.0									
Total amounts in this process (all QCs) status quo	100+75+40 =215	50+25+30 =105	25+25+30 =70.0	50+20+10 =80								
Total emissions, status quo (all QCs)	470											

Figure 19 shows the corresponding GHG emissions-based Sankey diagram. Again, all emissions are allocated to the product, which explains why the emissions related to waste management flow towards the QCs, respectively.

Figure 19: MFCA Sankey diagram, status quo—GHG emissions-based flows



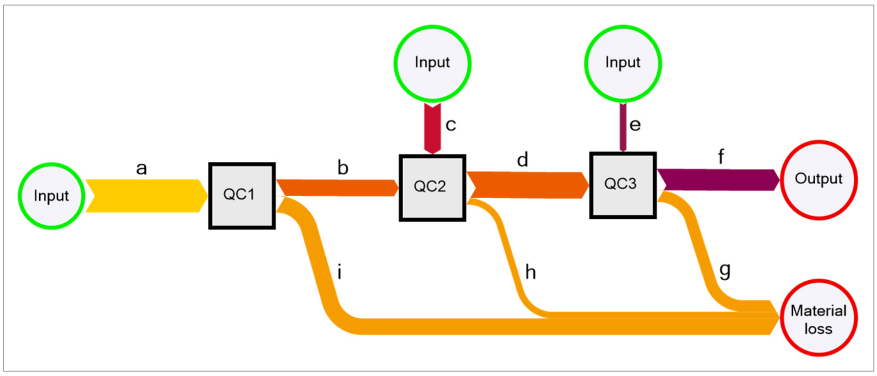
While it is easy to understand that the raw material and energy inputs cause emissions, the emission factors for system costs and waste management costs may not be as clear. First of all, it should be noted that the quantification of emission factors usually comprises some inaccuracy and uncertainty. This should not impede their use. However, it should be taken as instruction to review the results in this regard and, for example, handle decimal places accordingly. The efforts subsumed under the category *system* cover the processing and handling of the materials required for the production processes such as depreciation and maintenance of the production facilities. These aspects can be expressed with an emission factor that is estimated with the help of manufacturing or supplier specifications and employees who are familiar with the production facilities. Once this kind of indicator has been established, there may be industry-specific values one can refer to. In a similar manner, waste management usually requires logistics processes and specific treatments such as hazardous waste disposal that imply GHG emissions. The values can be estimated based on information from the disposal companies. Emission databases (cf. Subsection 4.3.1) can also be a source of help. Since their scope is likely to grow in the near future in light of the pressing need to reduce GHG emissions, this increases the probability of finding suitable data. If still no useful information can be found, it may be legitimate to make rough estimations as a first step and then examine the relevance of these elements compared to the values of the material and energy inputs in a second step, i.e., with a sensitivity analysis. Depending on the values, the categories *system environment* and *waste management* can hence make up a relevant share of the costs included in the MFCA 2.0 analysis. The influence of potential improvement measures in the form of GHG emission saving potential can now be evaluated with the MFCA 2.0 method.

The following cases imply the condition that the quantity of the product flow of 90 kg remains constant. When applying the method, the product flow can be changed as well and in return, another flow can be held constant. In order to keep the following cases consistent, the product flow remains unchanged. Therefore, the change in the material loss flows in the following paragraphs does not impact the product volume, but only the input and intermediate flows. This represents the entrepreneurial thought that a certain product amount shall be produced with the smallest efforts possible under the existing production conditions. Therefore, potential improvement measures do not affect the product amount or flow. This also reflects the concept of resource efficiency as defined in the VDI 4800 Part 1 as the quotient of benefit (product, function, functional unit) and need or effort (use of natural resources) (VDI, 2016, p. 12). The quotient can either be increased by increasing the nominator, i.e., the benefit (product, function, functional unit), or by decreasing the denominator, i.e., the need or effort (use of natural resources). Under the condition that the product amount of 90 kg remains constant, different changes in the system under analysis will be calculated and illustrated in the following.

4.3.4.2 Derivation of the Equations for the Saving Potential Under Linear Conditions

The saving potentials as a result of one or multiple material loss reductions can be calculated with specific saving factors. They will be explained using the general model in Figure 20. The model comprises three QCs, one loss flow per QC and it shows material flows only. The saving factors will be derived in the following Subparagraphs 4.3.4.2.1, 4.3.4.2.2 and 4.3.4.2.3.

Figure 20: Sankey diagram of a generic MFCA flow model with three QCs



The calculations are subject to the condition that all flows in the system under analysis are in a linear relationship with each other. That means that the ratios between the amount of energy and output flows as well as system costs and output flows are constant in the different QCs. For example, the mass-specific energy input stays constant, i.e., the energy demand in kWh per kg material input is the same in the improved scenario for each QC, respectively. As a result, the input flows of a particular QC change linearly with the reduction of a loss flow being the result of an improvement measure. If this is not the case and shall not be the condition of an MFCA 2.0 analysis, the following equations will not quantify the correct scenario-based saving potential. Instead, the saving potentials need to be quantified as will be shown in Subsection 4.3.6 for a non-linear example.

In a specific example, the correct saving factor for a QC is the one that includes the exact number of direct—i.e., induced by an improvement measure—material loss flow reductions that occur in this QC and in the following QCs. A material loss reduction as a consequence of another loss reduction would then be an indirect effect. For instance, if exactly one material loss flow gets directly reduced, *saving factor 1* needs to be applied to all input flows of that specific QC and to all input flows of the QCs that appear before that QC with regard to the direction of material flow. If two material loss flows in two different QCs get directly reduced at the same time, two saving factors are required. *Saving factor 2* is required to calculate the saving potential of the inputs of the

QC in which the *first* material loss appears in the direction of material flow and the input flows of all preceding QCs. Additionally, *Saving factor 1* is applied only to the inputs of the QC that appears *second* in the direction of material flow and the input flows of the preceding QC before the *first* material loss reduction occurs. The reduction of direct material losses is defined with the following variables *x*, *y* and *z*:

x: reduction of material loss flow *g* [%]
y: reduction of material loss flow *h* [%]
z: reduction of material loss flow *i* [%]

4.3.4.2.1 One Loss Flow Gets Reduced

The following derivation applies to material loss flow *g* in the example, but it can also be transferred to material loss flows *h* or *i* under the condition that exactly one material loss flow gets directly reduced. Equation (4.1) is required to calculate the corresponding saving factor with the scenario-based approach, and it can be derived using the input flow *a* as follows:

$$a_{saving\ potential\ g} = a_{status\ quo} - a_{improved\ g}$$
$$a_{saving\ potential\ g} = a_{status\ quo} - a_{status\ quo} \cdot improvement\ factor_g$$
$$a_{saving\ potential\ g} = a_{status\ quo} - a_{status\ quo} \cdot \left(1 - \frac{g \cdot x}{d + e}\right)$$
$$a_{saving\ potential\ g} = a_{status\ quo} \cdot \left(1 - \left(1 - \frac{g \cdot x}{d + e}\right)\right)$$
$$a_{saving\ potential\ g} = a_{status\ quo} \cdot \left(1 - 1 + \frac{g \cdot x}{d + e}\right)$$
$$a_{saving\ potential\ g} = a_{status\ quo} \cdot \frac{g \cdot x}{d + e}$$

Saving factor 1, with which $a_{status\ quo}$ is multiplied, is defined as follows:

$$saving\ factor\ 1 = \frac{g \cdot x}{d + e} \tag{4.1}$$

4.3.4.2.2 Two Loss Flows Get Reduced

If there is a second loss flow besides loss flow *g* in the example that can be reduced—named *h* in the example—the quantification of the reduction potential requires *saving factor 1* in order to determine the additional saving potential caused by the reduction of the second material loss flow. *Saving factor 2* can be derived as follows:

$$a_{saving\ potential\ g+h} = a_{status\ quo} - a_{improved\ g+h}$$
$$a_{saving\ potential\ g+h} = a_{status\ quo} - a_{improved\ g} \cdot improvement\ factor_h$$
$$a_{saving\ potential\ g+h} = a_{status\ quo} - a_{status\ quo} \cdot improvement\ factor_g \cdot improvement\ factor_h$$
$$a_{saving\ potential\ g+h} = a_{status\ quo} \cdot (1 - improvement\ factor_g \cdot improvement\ factor_h)$$
$$a_{saving\ potential\ g+h} = a_{status\ quo} \cdot \left(1 - \left(1 - \frac{g \cdot x}{d + e}\right) \cdot \left(1 - \frac{h \cdot \left(1 - \frac{g \cdot x}{d + e}\right) - h \cdot (1 - y)}{(b + c) \cdot \left(1 - \frac{g \cdot x}{d + e}\right)}\right)\right)$$

Saving factor 2, with which $a_{status\ quo}$ is multiplied, can now be defined. *Saving factor 1* is marked with a grey background in the following equation (4.2):

$$saving\ factor\ 2 = 1 - \left(1 - \frac{g \cdot x}{d+e}\right) \cdot \left(1 - \frac{h \cdot \left(1 - \frac{g \cdot x}{d+e}\right) - h \cdot (1-y)}{(b+c) \cdot \left(1 - \frac{g \cdot x}{d+e}\right)}\right) \tag{4.2}$$

4.3.4.2.3 Three Loss Flows Get Reduced

If three loss flows can be reduced (*g*, *h* and *i* in the example) at the same time, *saving factor 2* and hence also *saving factor 1* are required in order to calculate the correct saving potential. *Saving factor 3* can be derived as follows:

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} - a_{improved\ g+h+i}$$

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} - a_{improved\ g+h} \cdot improvement\ factor_i$$

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} - a_{improved\ g} \cdot improvement\ factor_h \cdot improvement\ factor_i$$

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} - a_{status\ quo} \cdot improvement\ factor_g \cdot improvement\ factor_h \cdot improvement\ factor_i$$

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} \cdot (1 - improvement\ factor_g \cdot improvement\ factor_h \cdot improvement\ factor_i)$$

$$a_{saving\ potential\ g+h+i} = a_{status\ quo} \cdot 1 - \left(1 - \frac{g \cdot x}{d+e}\right) \cdot \left(1 - \frac{h \cdot \left(1 - \frac{g \cdot x}{d+e}\right) - h \cdot (1-y)}{(b+c) \cdot \left(1 - \frac{g \cdot x}{d+e}\right)}\right) \cdot \left(1 - \frac{i \cdot \left(1 - \frac{g \cdot x}{d+e}\right) \cdot (1 - \frac{h \cdot \left(1 - \frac{g \cdot x}{d+e}\right) - h \cdot (1-y)}{(b+c) \cdot \left(1 - \frac{g \cdot x}{d+e}\right)}) - i \cdot (1-z)}{a \cdot \left(1 - \frac{\mathrm{g} \cdot \mathrm{x}}{\mathrm{d}+\mathrm{e}}\right) \cdot \left(1 - \frac{\mathrm{h} \cdot \left(1 - \frac{\mathrm{g} \cdot \mathrm{x}}{\mathrm{d}+\mathrm{e}}\right) - h \cdot (1-y)}{(\mathrm{b}+\mathrm{c}) \cdot \left(1 - \frac{\mathrm{g} \cdot \mathrm{x}}{\mathrm{d}+\mathrm{e}}\right)}\right)}\right)$$

Saving factor 3, with which $a_{status\ quo}$ is multiplied, can now be defined. *Saving factor 2* is marked with a grey background in the following equation (4.3):

$$\begin{aligned} &saving\ factor\ 3 \\ &= 1-\left(1-\frac{g\cdot x}{d+e}\right)\cdot\left(1-\frac{h\cdot\left(1-\frac{g\cdot x}{d+e}\right)-h\cdot(1-y)}{(b+c)\cdot\left(1-\frac{g\cdot x}{d+e}\right)}\right) \\ &\cdot\left(1-\frac{i\cdot\left(1-\frac{g\cdot x}{d+e}\right)\cdot\left(1-\frac{h\cdot\left(1-\frac{g\cdot x}{d+e}\right)-h\cdot(1-y)}{(b+c)\cdot\left(1-\frac{g\cdot x}{d+e}\right)}\right)-i\cdot(1-z)}{a\cdot\left(1-\frac{g\cdot x}{d+e}\right)\cdot\left(1-\frac{h\cdot\left(1-\frac{g\cdot x}{d+e}\right)-h\cdot(1-y)}{(b+c)\cdot\left(1-\frac{g\cdot x}{d+e}\right)}\right)}\right) \end{aligned} \tag{4.3}$$

4.3.4.3 Case 1: One Material Loss Flow Can Be Avoided Completely

The first case conducts an MFCA analysis and determines the saving potential under the condition that one material loss flow of the three can be avoided completely. The calculations require an efficiency improvement in the affected QC in which the loss can be avoided completely. The efficiency improvement is based on the ratio of the material loss reduction (numerator) and the total material input of the affected QC in which the loss reduction is implemented (denominator). Equation (4.1) leads to saving factor 1 for this case.

Case 1.1: Material Loss in QC1 Can Be Avoided Completely

$$saving\ factor\ 1 = \frac{50.00\ kg\cdot 100\%}{100.00\ kg}$$

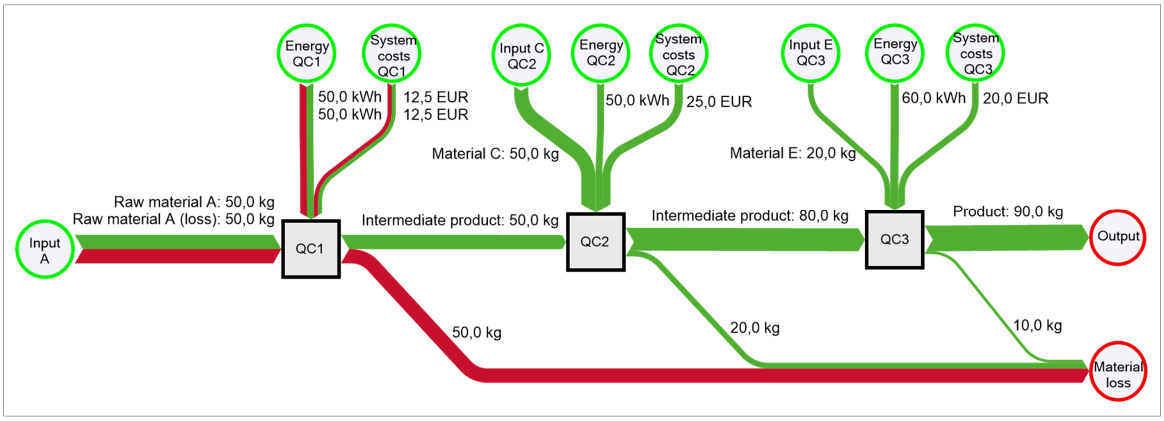
$$saving\ factor\ 1 = 50\%$$

Since QC1 is the first QC in the system under analysis, there is no preceding QC that could be affected. Therefore, saving factor 1 can directly be used to calculate the saving potentials. The saving factor 1 of 50% can thus be applied to the input flows in QC1. Since there is no other QC affected, the factor corresponds to the allocation factor for the material loss of the QC following ISO 14051.

Material:	100.00 kg·50%	= **50.00 kg**
Energy:	100.00 kWh·50%	= **50.00 kWh**
System costs:	25.00 EUR·50%	= **12.50 EUR**

If the material loss in QC1 can be eliminated, the material input can be reduced by **50.00 kg** (raw material A), the energy demand reduces by **50.00 kWh** and the system costs reduce by **12.50 EUR**. Figure 21 shows the physical saving potentials with the red shares of the flows.

Figure 21: MFCA 2.0 Sankey diagram, material loss in QC1 is avoided—physical flows

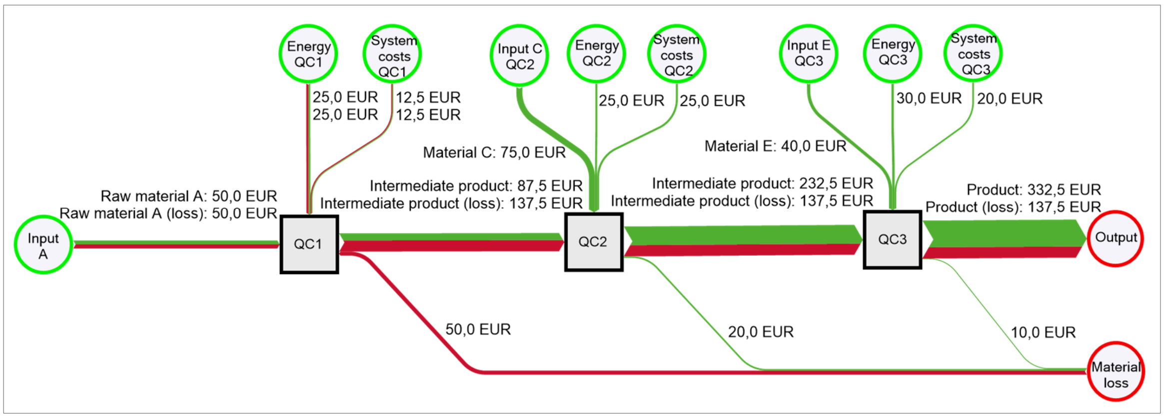


The multiplication with the cost factors leads to the monetary saving potentials of this case.

Material costs:	50.00 kg·1.00 EUR/kg	= 50.00 EUR
Energy costs:	50.00 kWh·0.50 EUR/kWh	= 25.00 EUR
System costs:	12.50 EUR	= 12.50 EUR
Waste management costs:	50.00 kg·100%·1.00 EUR/kg	= 50.00 EUR
		∑ = **137.50 EUR**

The monetary saving potential for the case that the material loss in QC1 is avoided equals **137.50 EUR**. Figure 22 shows the Sankey diagram with the monetary flows; the total saving potential for the case that the material loss in QC1 is avoided can be read off from the red share of the product flow.

Figure 22: MFCA 2.0 Sankey diagram, material loss in QC1 is avoided—monetary flows

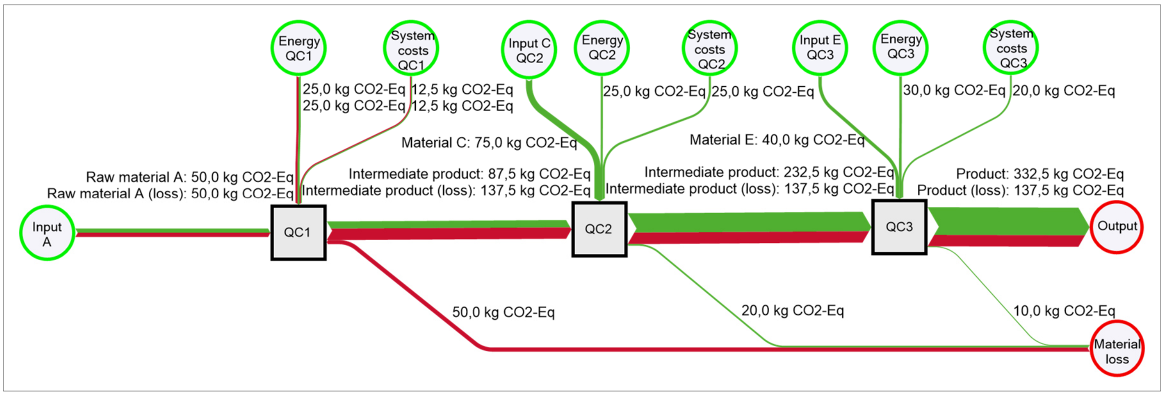


The GHG emissions-based saving potentials of this case can be quantified with the help of the GHG emission factors, leading to the following calculations.

Material:	50.00 kg·1.00 kg CO_2e/kg	= 50.00 kg CO_2e
Energy:	50.00 kWh·0.50 CO_2e /kWh	= 25.00 kg CO_2e
System costs:	12.50 EUR·1.00 CO_2e/EUR	= 12.50 kg CO_2e
Waste management:	50.00 kg·100%·1.00 CO_2e/kg	= 50.00 kg CO_2e
		∑ = **137.50 kg CO_2e**

If the material loss in QC1 can be avoided, GHG emissions can be reduced by **137.50 kg CO_2e**. Figure 23 shows the Sankey diagram with the GHG emissions-based flows. The red share of the product flow displays the total GHG emissions saving potential for the case that the material loss in QC1 is avoided.

Figure 23: MFCA 2.0 Sankey diagram, material loss in QC1 is avoided—GHG emissions-based flows



Case 1.2: Material Loss in QC2 Can Be Avoided Completely

$$saving\ factor\ 1 = \frac{20.00\ kg \cdot 100\%}{50.00\ kg + 50.00\ kg}$$

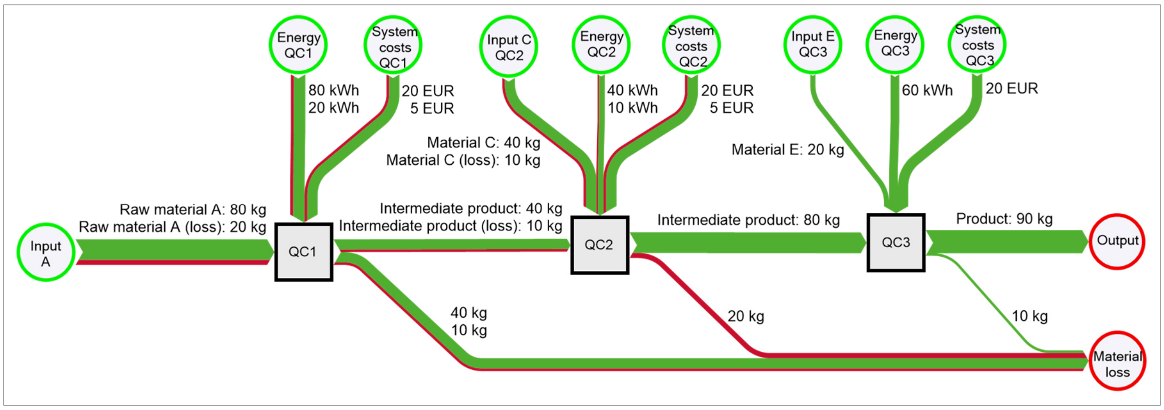
$$saving\ factor\ 1 = 20\%$$

QC2 follows QC1 and hence has a preceding quantity center. The saving potential consists of two summands because two QCs are affected. If the material loss in QC2 can be eliminated completely, the material efficiency of QC2 increases from 80% to 100%. Consequently, the saving of 20% can be realized for all input flows in QC1 and QC2. QC3 remains unaffected by these changes because improvements only affect the flows in the model that appeared before the improvement which regard to the direction of the material flow.

Material:	QC1: 100.00 kg·20%	= 20.00 kg
	QC2: 50.00 kg·20%	= 10.00 kg
		∑ = **30.00 kg**
Energy:	QC1: 100.00 kWh·20%	= 20.00 kWh
	QC2: 50.00 kWh·20%	= 10.00 kWh
		∑ = **30.00 kWh**
System costs:	QC1: 25.00 EUR·20%	= 5.00 EUR
	QC2: 25.00 EUR·20%	= 5.00 EUR
		∑ = **10.00 EUR**

The elimination of the material loss in QC2 leads to a reduction of the material demand by **30.00 kg** (20.00 kg material A and 10.00 kg material C), a reduction of energy demand by **30.00 kWh**, and a reduction of system costs by **10.00 EUR**. These saving potentials are shown by the red shares in the following Figure 24. As indicated, the material loss in QC1 reduces by 10.00 kg from 50.00 kg to 40.00 kg although the efficiency of QC1 has not changed. Nevertheless, the improvement of QC2 through the elimination of the material loss in QC2 leads to secondary effects on the preceding QC and its input flows, thereby in turn reducing that QC's material loss, too.

Figure 24: MFCA 2.0 Sankey diagram, material loss in QC2 is avoided—physical flows



The monetary saving potentials can be derived as the product of the physical values with the cost factors.

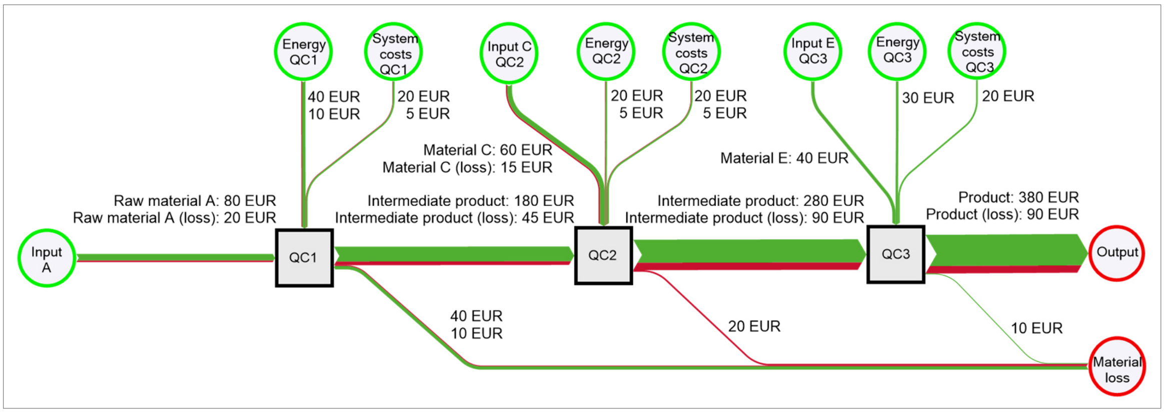
Material costs:	QC1: 20.00 kg·1.00 EUR/kg	= 20.00 EUR
	QC2: 10.00 kg·1.50 EUR/kg	= 15.00 EUR
		∑ = **35.00 EUR**
Energy costs:	QC1: 20 kWh·0.50 EUR/kWh	= 10.00 EUR
	QC2: 10 kWh·0.50 EUR/kWh	= 5.00 EUR
		∑ = **15.00 EUR**
System costs:	QC1: 5.00 EUR	= 5.00 EUR
	QC2: 5.00 EUR	= 5.00 EUR
		∑ = **10.00 EUR**

The reduction of waste management costs can be calculated with the help of saving factor 1 for QC1 and the factor 100% for QC2 since the elimination of the material loss flow in QC2 is the initiating change in this case.

Waste management costs:	QC1: 50.00 kg·20%·1.00 EUR/kg	= 10.00 EUR
	QC2: 20.00 kg·100%·1.00 EUR/kg	= 20.00 EUR
	∑	= **30.00 EUR**

In sum, the saving potential associated with the elimination of the material loss in QC2 amounts to **90.00 EUR**. Figure 25 includes the Sankey diagram from a cost perspective. The red shares illustrate the saving potential of the different input flows, adding up to the total amount of 90.00 EUR indicated in the final product flow.

Figure 25: MFCA 2.0 Sankey diagram, material loss in QC2 is avoided—monetary flows

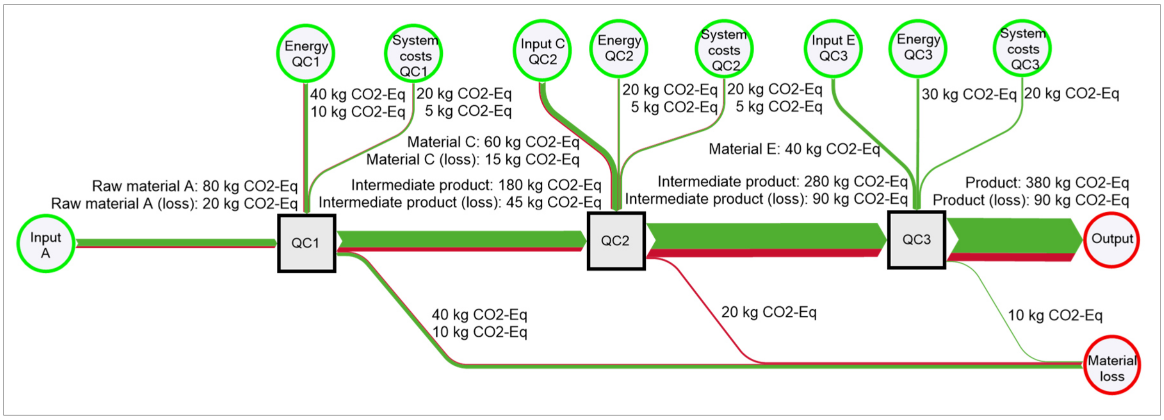


The GHG emissions-based reductions that are possible as a consequence of the material loss reduction in QC2 can be derived with the help of the GHG emission factors:

Material:	QC1: 20.00 kg·1.00 kg CO_2e/kg	= 20.00 kg CO_2e
	QC2: 10.00 kg·1.50 CO_2e /kg	= 15.00 kg CO_2e
	∑	= **35.00 kg** CO_2e
Energy:	QC1: 20.00 kWh·0.50 CO_2e/kWh	= 10.00 kg CO_2e
	QC2: 10.00 kWh·0.50 CO_2e/kWh	= 5.00 kg CO_2e
	∑	= **15.00 kg CO_2e**
System costs:	QC1: 5.00 EUR·1.00 kg CO_2e/EUR	= 5.00 kg CO_2e
	QC2: 5.00 EUR·1.00 kg CO_2e/EUR	= 5.00 kg CO_2e
	∑	= **10.00 kg CO_2e**
Waste management:	QC1: 50.00 kg·20%·1.00 kg CO_2e/kg	= 10.00 kg CO_2e
	QC2: 20.00 kg·100%·1.00 kg CO_2e//kg	= 20.00 kg CO_2e
	∑	= **30.00 kg CO_2e**

The saving potential for the case that the material loss in QC2 can be avoided sums up to **90.00 kg CO_2e**. Figure 26 shows the Sankey diagram and the corresponding GHG emissions-based values. The red shares visualize the saving potentials resulting from the elimination of the material loss in QC2, leading to the total amount of 90.00 kg indicated in the final product flow.

Figure 26: MFCA 2.0 Sankey diagram, material loss in QC2 is avoided—GHG emissions-based flows



Case 1.3: Material Loss in QC3 Can Be Avoided Completely

$$saving\ factor\ 1 = \frac{10.00\ kg \cdot 100\%}{80.00\ kg + 20.00\ kg}$$

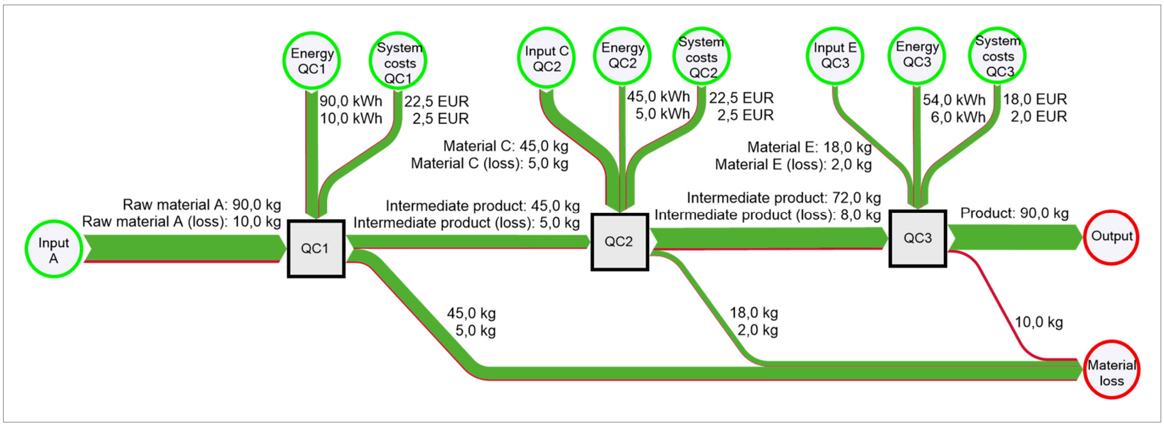
$$saving\ factor\ 1 = 10\%$$

QC3 is the last QC in the process under analysis, and it follows QC 1 and QC2. If the material losses in QC3 can be eliminated, it has impacts on the two other QCs. The saving potential of 10% can therefore be applied to all preceding input flows.

Material:	QC1: 100.00 kg·10%	= 10.00 kg
	QC2: 50.00 kg·10%	= 5.00 kg
	QC3: 20.00 kg·10%	= 2.00 kg
		∑ = **17.00 kg**
Energy:	QC1: 10.000 kWh·10%	= 10.00 kWh
	QC2: 50.00 kWh·10%	= 5.00 kWh
	QC3: 60.00 kWh·10%	= 6.00 kWh
		∑ = **21.00 kWh**
System costs:	QC1: 25.00 EUR·10%	= 2.50 EUR
	QC2: 25.00 EUR·10%	= 2.50 EUR
	QC3: 20.00 EUR·10%	= 2.00 EUR
		∑ = **7.00 EUR**

If the material loss in QC3 can be eliminated, the system's material demand decreases by **17.00 kg** (10.00 kg for material A, 5.00 kg for material C and 2.00 kg for material E), the energy demand is reduced by **21.00 kWh**, and the system costs reduce by **7.00 EUR**. These saving potentials are illustrated in the following Figure 27, highlighted in red color.

Figure 27: MFCA 2.0 Sankey diagram, material loss in QC3 is avoided—physical flows



To quantify the cost and GHG emissions saving potentials, the physical flows need to be multiplied with the cost factors and GHG emission factors as follows:

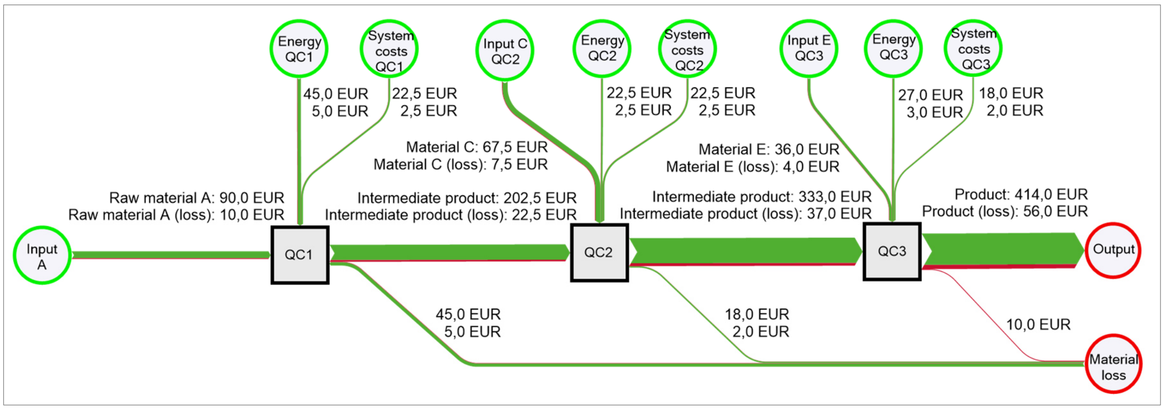
Material costs:	QC1: 10.00 kg·1.00 EUR/kg	= 10.00 EUR
	QC2: 5.00 kg·1.50 EUR/kg	= 7.50 EUR
	QC3: 2.00 kg·2.00 EUR/kg	= 4.00 EUR
		∑ = **21.50 EUR**
Energy costs:	QC1: 10.00 kWh·0.50 EUR/kWh	= 5.00 EUR
	QC2: 5.00 kWh·0.50 EUR/kWh	= 2.50 EUR
	QC3: 6.00 kWh·0.50 EUR/kWh	= 3.00 EUR
		∑ = **10.50 EUR**
System costs:	QC1: 2.50 EUR	= 2.50 EUR
	QC2: 2.50 EUR	= 2.50 EUR
	QC3: 2.00 EUR	= 2.00 EUR
		∑ = **7.00 EUR**

The reduction of waste management costs can be quantified as the product of the respective reduction of the material loss flow and saving factor 1. Because the loss flow of 10.00 kg in QC3 is the initiating measure for the case that can be avoided completely, it gets multiplied with 100%. The material loss flows of QC1 and QC2 need to be multiplied with saving factor 1:

Waste management costs:	QC1: 50.00 kg·10%·1.00 EUR/kg	= 5.00 EUR
	QC2: 20.00 kg·10%·1.00 EUR/kg	= 2.00 EUR
	QC3: 10.00 kg·100%·1.00 EUR/kg	= 10.00 EUR
		∑ = **17.00 EUR**

The total cost saving potential for the case that the material loss in QC3 can be avoided amounts to **56.00 EUR** as can be seen in Figure 28. The red share of the product flow indicates the total saving potential for this case.

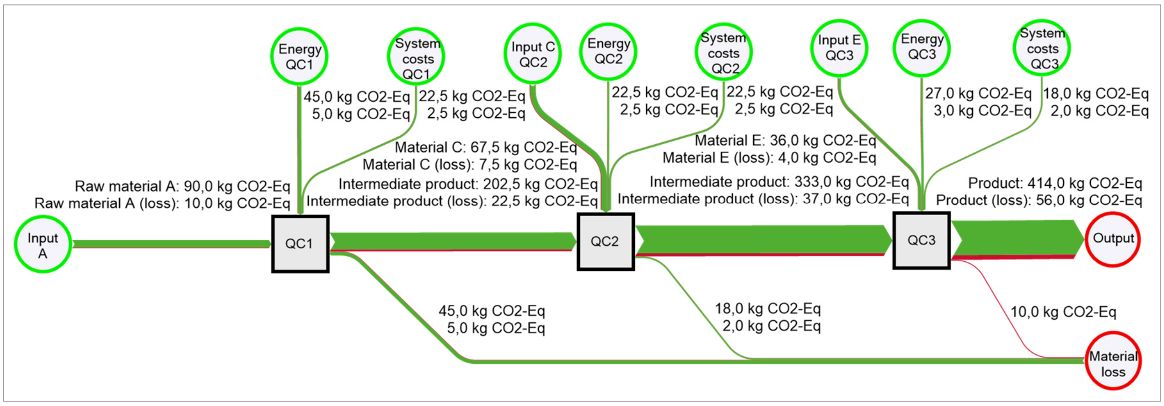
Figure 28: MFCA 2.0 Sankey diagram, material loss in QC3 is avoided—monetary flows



Material:	QC1: 10.00 kg·1.00 kg CO_2e/kg	= 10.00 kg CO_2e
	QC2: 5.00 kg·1.50 kg CO_2e/kg	= 7.50 kg CO_2e
	QC3: 2.00 kg·2.00 kg CO_2e /kg	= 4.00 kg CO_2e
		∑ = **21.50 kg CO_2e**
Energy:	QC1: 10.00 kWh·0.50 kg CO_2e/kWh	= 5.00 kg CO_2e
	QC2: 5.00 kWh·0.50 kg CO_2e/kWh	= 2.50 kg CO_2e
	QC3: 6.00 kWh·0.50 kg CO_2e/kWh	= 3.00 kg CO_2e
		∑ = **10.50 kg CO_2e**
System costs:	QC1: 2.50 EUR·1.00 kg CO_2e/EUR	= 2.50 kg CO_2e
	QC2: 2.50 EUR·1.00 kg CO_2e/EUR	= 2.50 kg CO_2e
	QC3: 2.00 EUR·1.00 kg CO_2e/EUR	= 2.00 kg CO_2e
		∑ = **7.00 kg CO_2e**
Waste management:	QC1: 50.00 kg·10%·1.00 kg CO_2e/kg	= 5.00 kg CO_2e
	QC2: 20.00 kg·10%·1.00 kg CO_2e /kg	= 2.00 kg CO_2e
	QC3: 10.00 kg·100%·1.00 kg CO_2e/kg	= 10.00 kg CO_2e
		∑ = **17.00 kg CO_2e**

The total GHG emissions-based saving potential for the case that the material loss in QC3 can be avoided amounts to **56.00 kg CO_2e** as can be read off in the following Figure 29 from the red share of the product flow.

Figure 29: MFCA 2.0 Sankey diagram, material loss in QC3 is avoided—GHG emissions-based flows



Based on the calculations that were carried out for Case 1, the following statements can be made:

1. If the material loss of 50.00 kg in QC1 can be avoided, 50.00 kg materials, 50.00 kWh energy, 12.50 EUR system costs and 50.00 EUR waste management costs can be avoided in the system under analysis. This leads to the monetary saving potential of 137.50 EUR. Moreover, 137.50 kg of GHG emissions (CO_2e) could be avoided.
2. If the material loss of 20.00 kg in QC2 can be avoided, 30.00 kg materials, 30.00 kWh energy, 10.00 EUR system costs and 30.00 EUR waste management costs can be avoided in the system under analysis. This equals the monetary saving potential of 90.00 EUR. Moreover, 90.00 kg of GHG emissions (CO_2e) could be avoided.
3. If the material loss of 10.00 kg in QC3 can be avoided, 17.00 kg materials, 21.00 kWh energy, 7.00 EUR system costs and 17.00 EUR waste management costs can be avoided in the system under analysis. The corresponding monetary saving potential amounts to 56.00 EUR. Moreover, 56.00 kg of GHG emissions (CO_2e) could be avoided.

Case 2 will describe how to calculate the saving potential if one material loss flow can be partly reduced.

4.3.4.4 Case 2: One Material Loss Flow Can Be Partly Reduced

Let us consider the case that one material flow can only be partly reduced. This case includes the following assumption: The material loss of 10.00 kg in QC3 can be reduced by 40%, leading to a reduced material loss flow of 6.00 kg. The corresponding saving potential can also be quantified based on the MFCA 2.0 algorithm. First of all, the improvement which the loss reduction causes, needs to be determined with (4.1) for saving factor 1:

$$saving\ factor\ 1 = \frac{10.00\ kg \cdot 40\%}{80.00\ kg + 20.00\ kg}$$

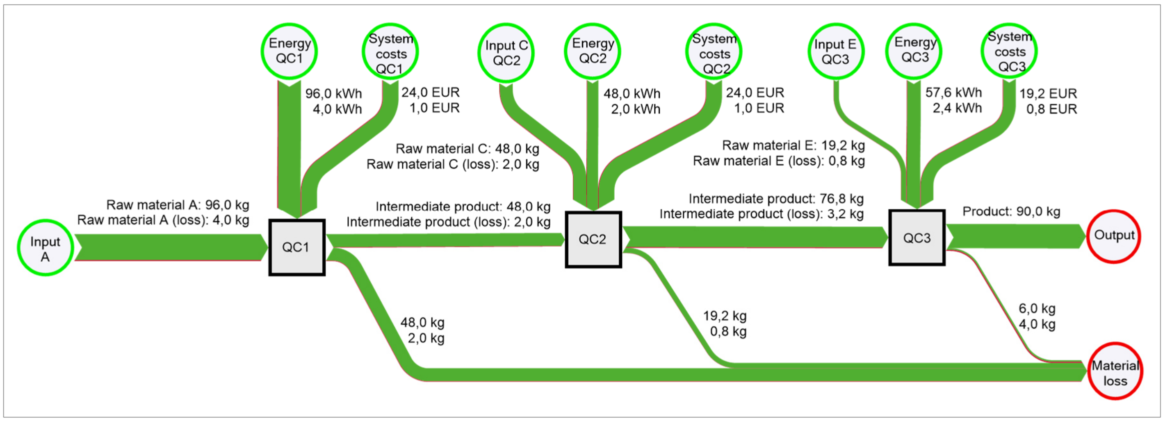
$$saving\ factor\ 1 = 4\%$$

Since QC3 follows QC1 and QC2, the improvement affects all three QCs. Therefore, the improvement factor of 4% can be applied to all preceding input flows. The saving potentials are quantified as follows:

Material:	QC1: 100.00 kg·4%	= 4.00 kg
	QC2: 50.00 kg·4%	= 2.00 kg
	QC3: 20.00 kg·4%	= 0.80 kg
		∑ = **6.80 kg**
Energy:	QC1: 100.00 kWh·4%	= 4.00 kWh
	QC2: 50.00 kWh·4%	= 2.00 kWh
	QC3: 60.00 kWh·4%	= 2.40 kWh
		∑ = **8.40 kWh**
System costs:	QC1: 25.00 EUR·4%	= 1.00 EUR
	QC2: 25.00 EUR·4%	= 1.00 EUR
	QC3: 20.00 EUR·4%	= 0.80 EUR
		∑ = **2.80 EUR**

If the material loss in QC3 can be reduced by 4 kg, this represents an improvement of all inputs in the system under analysis by 4%. As a result, material demand of the system reduces by **6.80 kg** (material A 4.00 kg, material B 2.00 kg and material C 0.80 kg), energy demand decreases by **8.40 kWh** and system costs reduce by **2.80 EUR**. The following Figure 30 includes the physical flow model of the status quo and the improved scenario combined in one Sankey diagram, which depicts the MFCA 2.0 approach. The red shares represent the saving potential of the input flows, respectively.

Figure 30: MFCA 2.0 Sankey diagram, material loss flow in QC3 is reduced by 4.00 kg—physical flows



The monetary saving potentials can be derived with the help of the cost and emission factors as follows:

Material costs:	QC1: 4.00 kg·1.00 EUR/kg	= 4.00 EUR
	QC2: 2.00 kg·1.50 EUR/kg	= 3.00 EUR
	QC3: 0.80 kg·2.00 EUR/kg	= 1.60 EUR
	∑	= **8.60 EUR**
Energy costs:	QC1: 4.00 kWh·0.50 EUR/kWh	= 2.00 EUR
	QC2: 2.00 kWh·0.50 EUR/kWh	= 1.00 EUR
	QC3: 2.40 kWh·0.50 EUR/kWh	= 1.20 EUR
	∑	= **4.20 EUR**
System costs:	QC1: 1.00 EUR	= 1.00 EUR
	QC2: 1.00 EUR	= 1.00 EUR
	QC3: 0.80 EUR	= 0.80 EUR
	∑	= **2.80 EUR**

To quantify the saved waste management costs, the loss flows of QC1 and QC2 each get multiplied with saving factor 1, which was calculated above. The material loss flow in QC3 is the initiating material loss reduction. Since it can be reduced by 40% in this case, the value of 40% is directly used to calculate the reduction of waste management costs in QC3:

Waste management costs:	QC1: 50.00 kg·4%·1.00 EUR/kg	= 2.00 EUR
	QC2: 20.00 kg·4%·1.00 EUR/kg	= 0.80 EUR
	QC3: 10.00 kg·40%·1.00 EUR/kg	= 4.00 EUR
	∑	= **6.80 EUR**

The total saving potential for the case that the material loss in QC3 can be reduced by 4.00 kg sums up to **22.40 EUR** for the system under analysis.

GHG emissions that can be avoided in this case are calculated with the help of the different input-specific emission factors.

Material:	QC1: 4.00 kg·1.00 CO_2e/kg	= 4.00 kg CO_2e
	QC2: 2.00 kg·1.50 CO_2e/kg	= 3.00 kg CO_2e
	QC3: 0.80 kg·2.00 CO_2e/kg	= 1.60 kg CO_2e
	∑	= **8.60 kg CO_2e**
Energy:	QC1: 4.00 kWh·0.50 kg CO_2e/kWh	= 2.00 kg CO_2e
	QC2: 2.00 kWh·0.50 kg CO_2e/kWh	= 1.00 kg CO_2e
	QC3: 2.40 kWh·0.50 kg CO_2e/kWh	= 1.20 kg CO_2e
	∑	= **4.20 kg CO_2e**
System costs:	QC1: 1.00 EUR·1.00 kg CO_2e/EUR	= 1.00 kg CO_2e
	QC2: 1.00 EUR·1.00 kg CO_2e/EUR	= 1.00 kg CO_2e
	QC3: 0.80 EUR·1.00 kg CO_2e/EUR	= 0.80 kg CO_2e
	∑	= **2.80 kg CO_2e**
Waste management:	QC1: 2.00 EUR·1.00 kg CO_2e/EUR	= 2.00 kg CO_2e
	QC2: 0.80 EUR·1.00 kg CO_2e/EUR	= 0.80 kg CO_2e
	QC3: 4.00 EUR·1.00 kg CO_2e/EUR	= 4.00 kg CO_2e
	∑	= **6.80 kg CO_2e**

If the material loss in QC3 is reduced by 4.00 kg—representing 40% of the material loss in QC3—**22.40 kg CO_2e** can be saved. The following two paragraphs will present cases in which two material loss flows can be reduced at the same time.

4.3.4.5 Case 3: Two Material Loss Flows Can Be Avoided Completely

In Case 3, the material losses in QC1 (50.00 kg) and QC3 (10.00 kg) can both be eliminated at once, i.e., they are reduced by 100% to 0.00 kg. The efficiency ratio of 80%—i.e., the loss rate of 20%—in QC2 stays unchanged. In order to combine the two material loss reductions, the factors need to be applied to the individual relevant flows. A reduction of a material loss flow only affects the flows that appear before that reduced material loss flow with regard to the direction of material flow in the process under analysis. Therefore, the material loss reduction of QC3 affects all input flows of QC3, QC2 and QC1, while the loss reduction in QC1 affects the input flows of QC1 only.

Following saving factor 2 included in (4.2) (see Paragraph 4.3.4.2), the following calculations lead to the saving factor that needs to be applied to the inputs of QC1, which appear before the material loss flows that are avoided in this case.

$$saving\ factor\ 2 = 1-\left(1-\frac{10\ kg\cdot 100\%}{80\ kg+20\ kg}\right)\cdot\left(1-\frac{50\ kg\cdot\left(1-\frac{10\ kg\cdot 100\%}{80\ kg+20\ kg}\right)-50\ kg\cdot(1-100\%)}{(50\ kg+50\ kg)\cdot\left(1-\frac{10\ kg\cdot 100\%}{80\ kg+20\ kg}\right)}\right)$$

$$saving\ factor\ 2 = 55\%$$

The input flows for the additional inputs in QC2 and QC3 are only subject to saving factor 1 because they occur after QC1 with regard to the direction of material flow. Saving factor 1 considers one material loss reduction only. Equation (4.1) represents saving factor 1, leading to the following results:

$$saving\ factor\ 1 = \frac{10.00\ kg\cdot 100\%}{80.00\ kg+20.00\ kg}$$

$$saving\ factor\ 1 = 10\%$$

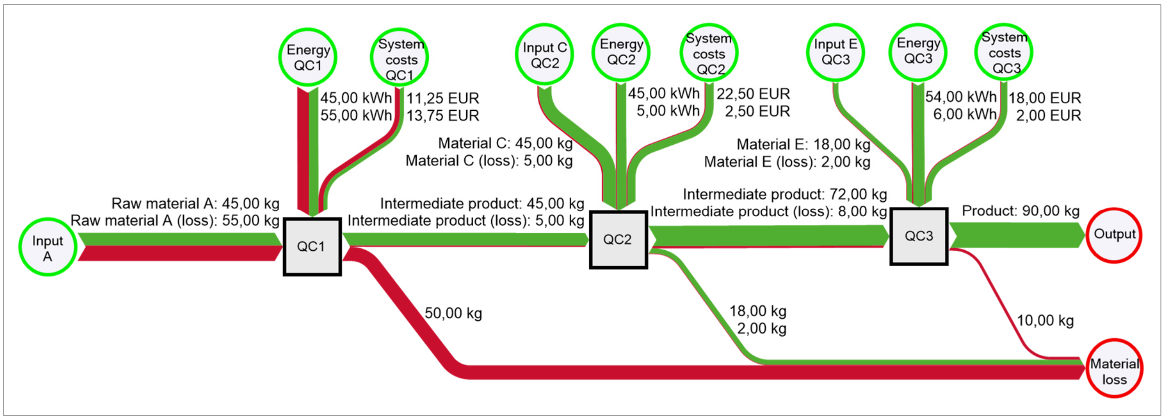
Material:	QC1: 100.00 kg·55%	= 55.00 kg
	QC2: 50.00 kg·10%	= 5.00 kg
	QC3: 20.00 kg·10%	= 2.00 kg
		∑ = **62.00 kg**

When calculating the energy saving potentials and system cost saving potentials, the improvement factors for the material saving potentials can be multiplied with the demand of the status quo of each QC as follows:

Energy:	QC1: 100.00 kWh·55%	= 55.00 kWh
	QC2: 50.00 kWh·10%	= 5.00 kWh
	QC3: 60.00 kWh·10%	= 6.00 kWh
		∑ = **66.00 kWh**
System costs:	QC1: 25.00 EUR·55%	= 13.75 EUR
	QC2: 25.00 EUR·10%	= 2.50 EUR
	QC3: 20.00 EUR·10%	= 2.00 EUR
		∑ = **18.25 EUR**

If the material loss flow in QC1 and QC3 can be avoided, **62.00 kg** of materials (55.00 kg of material A, 5.00 kg of material C and 2.00 kg of material E), **66.00 kWh** and **18.25 EUR** system costs can be saved in the analyzed system. Figure 31 visualizes the flows of this case and the saving potentials are marked with the red shares of the flows.

Figure 31: MFCA 2.0 Sankey diagram, material losses in QC1 and QC3 are avoided—physical flows



The monetary saving potentials can be determined as the result of the multiplication of the physical saving potentials with the cost factors:

Material costs:	QC1: 55.00 kg·1.00 EUR/kg	= 55.00 EUR
	QC2: 5.00 kg·1.50 EUR/kg	= 7.50 EUR
	QC3: 2.00 kg·2.00 EUR/kg	= 4.00 EUR
		∑ = **66.50 EUR**
Energy costs:	QC1: 55.00 kWh·0.50 EUR/kWh	= 27.50 EUR
	QC2: 5.00 kWh·0.50 EUR/kWh	= 2.50 EUR
	QC3: 6.00 kWh·0.50 EUR/kWh	= 3.00 EUR
		∑ = **33.00 EUR**

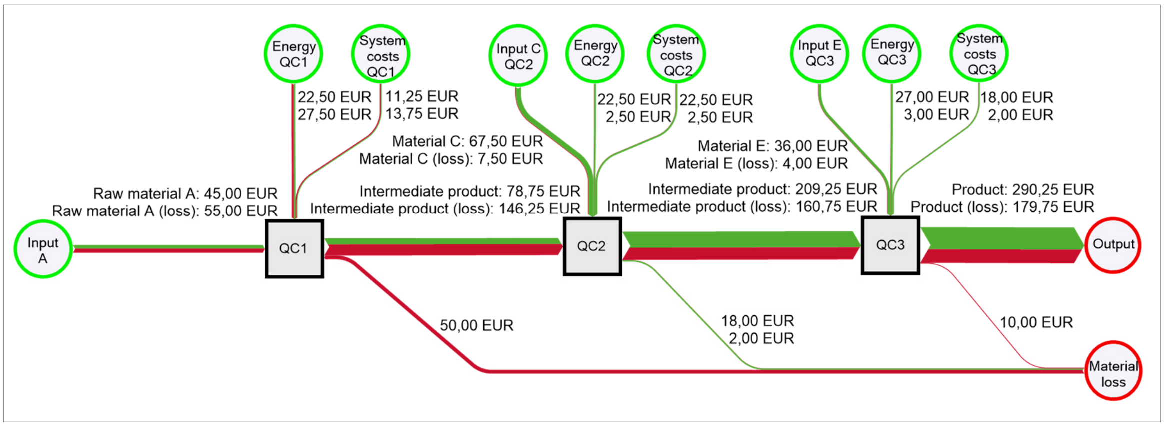
System costs:	QC1: 13.75 EUR	= 13.75 EUR
	QC2: 2.50 EUR	= 2.50 EUR
	QC3: 2.00 EUR	= 2.00 EUR
		∑ = **18.25 EUR**

The reduction of the waste management costs can be immediately calculated for QC1 and QC3 since these two material loss flows are actively eliminated in this case, i.e., the value of 50.00 kg in QC1 and 10.00 kg in QC3 can be immediately used. The loss flow in QC2 requires saving factor 1 resulting from the material loss reduction in QC3. The material loss reduction of QC1 does not affect the material loss flow of QC2 since it appears after the material loss flow in QC1 with regard to the direction of material flow.

Waste management costs:	QC1: 50.00 kg·1.00 EUR/kg	= 50.00 EUR
	QC2: 20.00 kg·10%·1.00 EUR/kg	= 2.00 EUR
	QC3: 10.00 kg·1.00 EUR/kg	= 10.00 EUR
		∑ = **62.00 EUR**

If the material loss flows in QC1 and in QC3 can be avoided, a total of **179.75 EUR** can be saved in the analyzed system. Figure 32 visualizes the flows of this case and the saving potentials are marked with the red shares of the flows. The product flow shows the total saving potential of 179.75 EUR.

Figure 32: MFCA 2.0 Sankey diagram, material losses in QC1 and QC3 are avoided—monetary flows



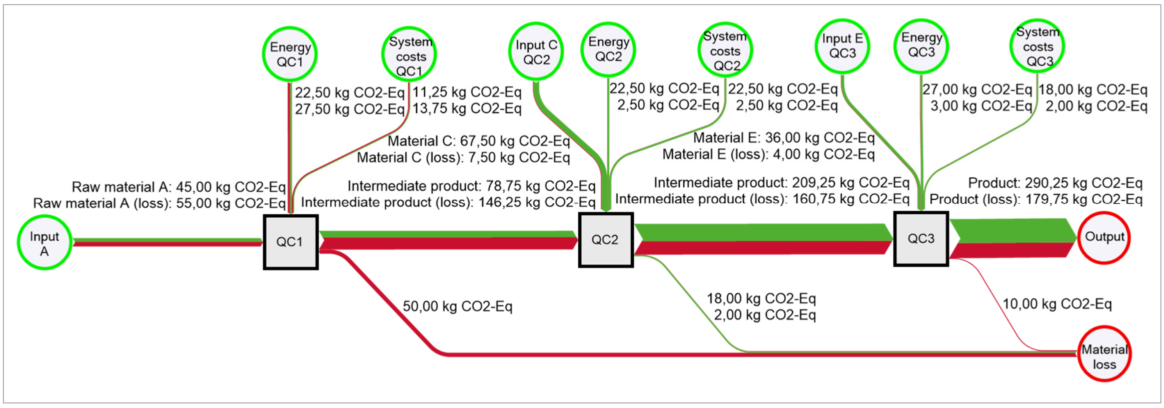
The GHG emission saving potential can be calculated based on the specific GHG emission factors:

Material:	QC1: 55 kg·1.00 kg CO_2e/kg	= 55.00 kg CO_2e
	QC2: 5 kg·1.50 kg CO_2e/kg	= 7.50 kg CO_2e
	QC3: 2 kg·2.00 kg CO_2e/kg	= 4.00 kg CO_2e
		∑ = **66.50 kg CO_2e**
Energy:	QC1: 55 kWh·0.50 kg CO_2e/kWh	= 27.50 kg CO_2e
	QC2: 5 kWh·0.50 kg CO_2e/kWh	= 2.50 kg CO_2e
	QC3: 6 kWh·0.50 kg CO_2e/kWh	= 3.00 kg CO_2e
		∑ = **33.00 kg CO_2e**

System costs:	QC1: 13.75 EUR·1.00 kg CO_2e/EUR	= 13.75 kg CO_2e
	QC2: 2.50 EUR·1.00 kg CO_2e/EUR	= 2.50 kg CO_2e
	QC3: 2.00 EUR·1.00 kg CO_2e/EUR	= 2.00 kg CO_2e
	$\sum$	**= 18.25 kg CO_2e**
Waste management:	QC1: 50.00 kg·1.00 EUR/kg	= 50.00 kg CO_2e
	QC2: 2.00 kg·1.00 EUR/kg	= 2.00 kg CO_2e
	QC3: 10.00 kg·1.00 EUR/kg	= 10.00 kg CO_2e
	$\sum$	**= 62.00 kg CO_2e**

If the material loss flows in QC1 and in QC3 can be avoided, **179.75 kg CO_2kg** system costs can be saved in the analyzed system. Figure 33 visualizes the flows of this case and the saving potentials are marked with the red shares of the flows. The total saving potential can be read off from the red share of the product flow on the right.

Figure 33: MFCA 2.0 Sankey diagram, material losses in QC1 and QC3 are avoided—GHG emissions-based flows



4.3.4.6 Case 4: Two Material Loss Flows Can Be Partly Reduced

This paragraph focuses on the case that two material loss flows can be reduced, but it is different from the previous case because the material losses cannot be avoided completely. They can only be partly reduced. Therefore, three material loss flows remain in the system under analysis. To exemplify the algorithms, the material loss flows will be reduced as follows:

- The material loss flow in QC1 gets reduced by 20.00 kg or 40% from 50.00 kg to 30.00 kg.
- The material loss flow in QC3 gets reduced by 2.00 kg or 20% from 10.00 kg to 8.00 kg.

The efficiency rate of 80% in QC2 remains unchanged. Just like in Case 3, the improvement factors resulting from the two material loss reductions need to be determined and applied to the corresponding flows. Whether a factor is relevant to a specific flow or not depends on whether the flow appears before the material loss flow that has been reduced or eliminated with regard to the direction of material flow. Only then, the specific saving factor should be applied to the flows. That is the reason why in the example, saving factor 2 as a result of equation (4.2) is applied to all input flows of QC1, and saving factor 1 is only applied to the input flows of QC2 and QC3.

$$saving\ factor\ 2 = 1 - \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) \cdot \left(1 - \frac{50\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) - 50\ kg \cdot (1 - 40\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)}\right)$$

$$saving\ factor\ 2 = 21\%$$

As only QC1 is affected by saving factor 2, QC2 and QC3 require improvement factor 1 to quantify the saving potentials of the input flows of these QCs. Saving factor 1 is the result of (4.1).

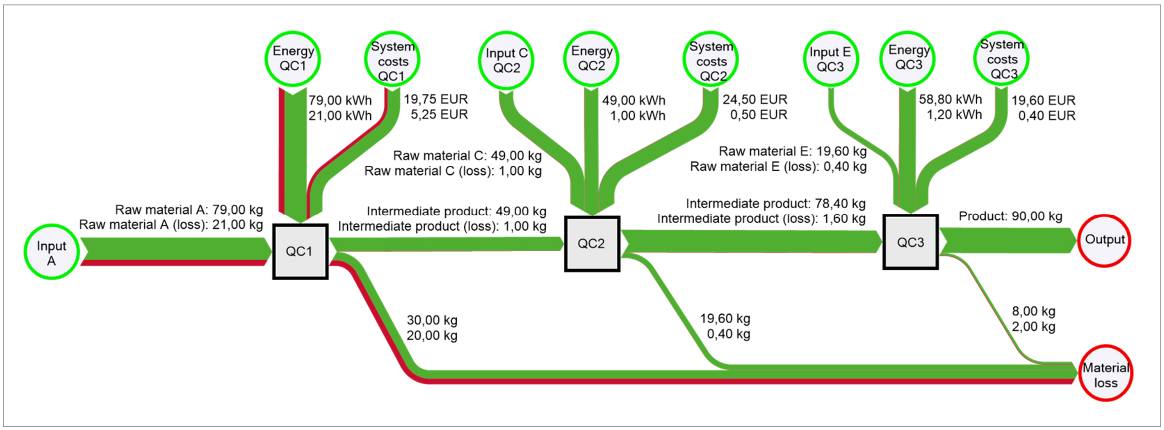
$$saving\ factor\ 1 = \frac{10.00\ kg \cdot 20\%}{80.00\ kg + 20.00\ kg}$$

$$saving\ factor\ 1 = 2\%$$

Material:	QC1: 100.00 kg·21%	= 21.00 kg
	QC2: 50.00 kg·2%	= 1.00 kg
	QC3: 20.00 kg·2%	= 0.40 kg
		∑ = **22.40 kg**
Energy:	QC1: 100.00 kWh·21%	= 21.00 kWh
	QC2: 50.00 kWh·2%	= 1.00 kWh
	QC3: 60.00 kWh·2%	= 1.20 kWh
		∑ = **23.20 kWh**
System costs:	QC1: 25.00 EUR·21%	= 5.25 EUR
	QC2: 25.00 EUR·2%	= 0.50 EUR
	QC3: 20.00 EUR·2%	= 0.40 EUR
		∑ = **6.15 EUR**

If the material loss flow in QC1 and QC3 can be reduced by 20.00 kg (QC1) and 2.00 kg (QC3), **22.40 kg** of materials (21.00 kg of material A, 1.00 kg of material C and 0.40 kg of material E), **23.20 kWh** and **6.15 EUR** system costs can be saved in the analyzed system. The Sankey diagram in the following Figure 34 depicts the MFCA 2.0 approach. It includes the two scenarios, and the red shares represent the reduction potential of the different flows, i.e., the saving potentials.

Figure 34: MFCA 2.0 Sankey diagram, material loss reduction in QC1 by 20.00 kg and in QC3 by 2.00 kg—physical flows



The corresponding costs that can be reduced based on the specific cost factors are the following:

Material costs:	QC1: 21.00 kg·1.00 EUR/kg	= 21.00 EUR
	QC2: 1.00 kg·1.50 EUR/kg	= 1.50 EUR
	QC3: 0.40 kg·2.00 EUR/kg	= 0.80 EUR
		$\sum$ = **23.30 EUR**
Energy costs:	QC1: 21.00 kWh·0.50 EUR/kg	= 10.50 EUR
	QC2: 1.00 kWh·0.50 EUR/kg	= 0.50 EUR
	QC3: 1.20 kWh·0.50 EUR/kg	= 0.60 EUR
		$\sum$ = **11.60 EUR**
System costs:	QC1: 5.25 EUR	= 5.25 EUR
	QC2: 0.50 EUR	= 0.50 EUR
	QC3: 0.40 EUR	= 0.40 EUR
		$\sum$ = **6.15 EUR**
Waste management costs:	QC1: 50.00 kg·40%·1.00 EUR/kg	= 20.00 EUR
	QC2: 20.00 kg·2%·1.00 EUR/kg	= 0.40 EUR
	QC3: 10.00 kg·20%·1.00 EUR/kg	= 2.00 EUR
		$\sum$ = **22.40 EUR**

A total of **63.45 EUR** can be saved if the material losses in QC1 are reduced by 40% from 50.00 kg to 40.00 kg and in QC3 by 20% from 10.00 kg to 8.00 kg.

Finally, the avoided GHG emissions can be quantified using the GHG emission factors:

Material:	QC1: 21.00 kg·1.00 kg CO_2e/kg	= 21.00 kg CO_2e
	QC2: 1.00 kg·1.50 kg CO_2e/kg	= 1.50 kg CO_2e
	QC3: 0.40 kg·2.00 kg CO_2e/kg	= 0.80 kg CO_2e
	∑	= **23.30 kg CO_2e**
Energy:	QC1: 21.00 kWh·0.50 kg CO_2e/kWh	= 10.50 kg CO_2e
	QC2: 1.00 kWh·0.50 kg CO_2e/kWh	= 0.50 kg CO_2e
	QC3: 1.20 kWh·0.50 kg CO_2e/kWh	= 0.60 kg CO_2e
	∑	= **11.60 kg CO_2e**
System costs:	QC1: 5.25 EUR·1.00 kg CO_2e/EUR	= 5.25 kg CO_2e
	QC2: 0.50 EUR·1.00 kg CO_2e/EUR	= 0.50 kg CO_2e
	QC3: 0.40 EUR·1.00 kg CO_2e/EUR	= 0.40 kg CO_2e
	∑	= **6.15 kg CO_2e**
Waste management:	QC1: 20 kg·1.00 kg CO_2e/kg	= 20.00 kg CO_2e
	QC2: 20 kg·2%·1.00 kg CO_2e/kg	= 0.40 kg CO_2e
	QC3: 2.00 kg·1.00 kg CO_2e/kg	= 2.00 kg CO_2e
	∑	= **22.40 kg CO_2e**

If the material loss in QC1 can be reduced by 10.00 kg from 50.00 kg to 40.00 kg and the material loss in QC3 can be reduced by 2.00 kg from 10.00 kg to 8.00 kg, the GHG emissions of the system under analysis will be reduced by **63.45 kg CO_2e**.

4.3.4.7 Case 5: All Three Material Losse Flows Can Be Avoided Completely

Case 5 represents the ideal case that all material losses and the corresponding loss flows in the system under MFCA analysis can be avoided completely. Since all material losses are avoided, the improved material efficiency for each single QC and thus for the whole process is 100%.

$$x = y = z = 100\%$$

The saving potential for the inputs in QC1 are quantified with (4.3) leading to saving factor 3:

$$
\begin{aligned}
&saving\ factor\ 3 \\
&= 1-\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)\cdot\left(1-\frac{20\,kg\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)-20\,kg\cdot(1-100\%)}{(50\,kg+50\,kg)\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)}\right) \\
&\cdot\left(1-\frac{50\,kg\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)\cdot\left(1-\frac{20\,kg\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)-20\,kg\cdot(1-100\%)}{(50\,kg+50\,kg)\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)}\right)-50\,kg\cdot(1-100\%)}{100\,kg\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)\cdot\left(1-\frac{20\,kg\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)-20\,kg\cdot(1-100\%)}{(50\,kg+50\,kg)\cdot\left(1-\frac{10\,kg\cdot 100\%}{80\,kg+20\,kg}\right)}\right)}\right)
\end{aligned}
$$

$$saving\ factor\ 3 = 64\%$$

The saving potential for the inputs in QC2 can be quantified with (4.2) as follows:

$$saving\ factor\ 2 = 1 - \left(1 - \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}\right) \cdot \left(1 - \frac{20\ kg \cdot \left(1 - \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}\right) - 20\ kg \cdot (1 - 100\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}\right)}\right)$$

$$saving\ factor\ 2 = 28\%$$

Finally, the saving potential for QC3 can be calculated with (4.1):

$$saving\ factor\ 1 = \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}$$

$$saving\ factor\ 1 = 10\%$$

Material:	QC1: 100.00 kg·64%	= 64.00 kg
	QC2: 50.00 kg·28%	= 14.00 kg
	QC3: 20.00 kg·10%	= 2.00 kg
		∑ **= 80.00 kg**
Energy:	QC1: 100.00 kWh·64%	= 64.00 kWh
	QC2: 50.00 kWh·28%	= 14.00 kWh
	QC3: 60.00 kWh·10%	= 6.00 kWh
		∑ **= 84.00 kWh**
System costs:	QC1: 25.00 EUR·64%	= 16.00 EUR
	QC2: 25.00 EUR·28%	= 7.00 EUR
	QC3: 20.00 EUR·10%	= 2.00EUR
		∑ **= 25.00 EUR**

Figure 35 shows the status quo, and Figure 36 shows the improved scenario of the model. Compared to the status quo, all three material loss flows are eliminated. Therefore, the efficiency of the system under analysis increases to the maximum of 100%. Consequently, all input flows can be reduced to a minimum under these process conditions. Figure 37 illustrates the scenario-based algorithm of MFCA 2.0 for this case with a Sankey diagram.

Figure 35: Sankey diagram of the MFCA model, status quo—physical flows

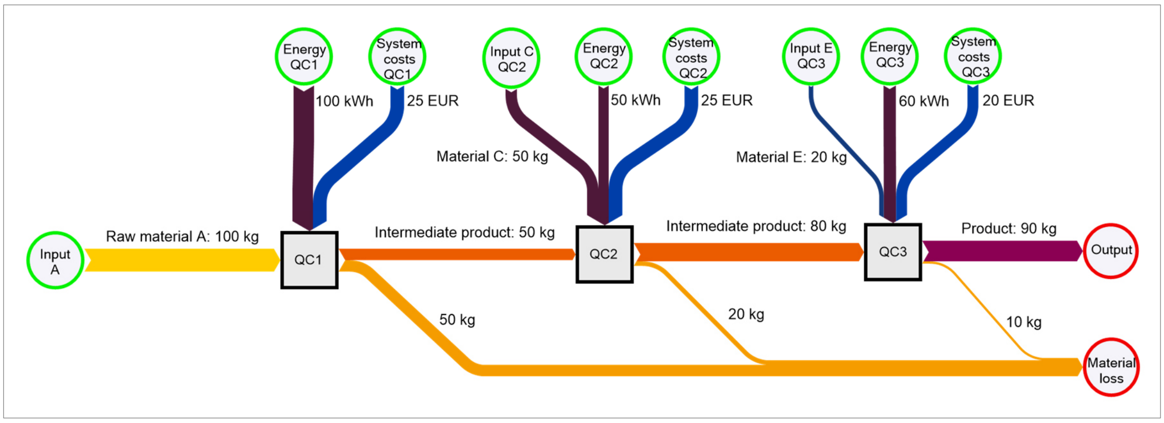


Figure 36: Sankey diagram of the MFCA model, improved scenario, all losses are avoided—physical flows

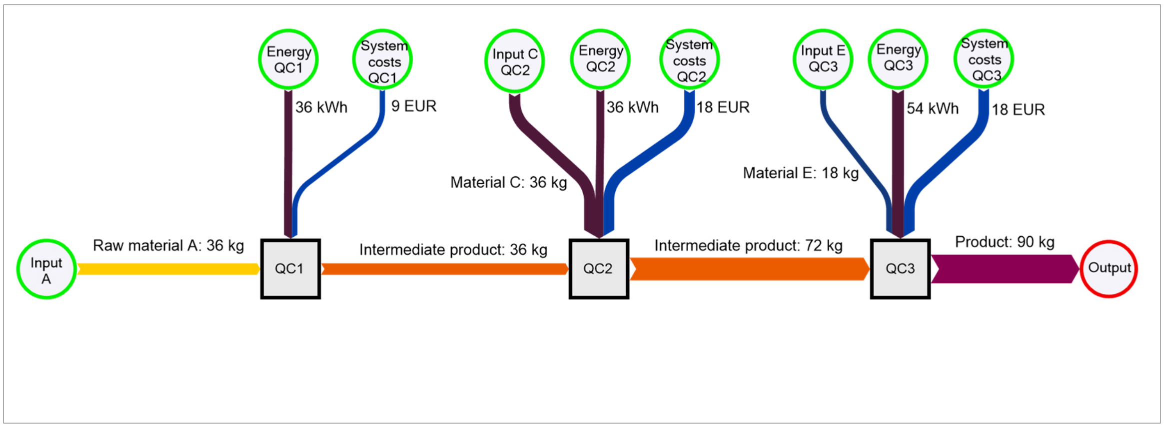
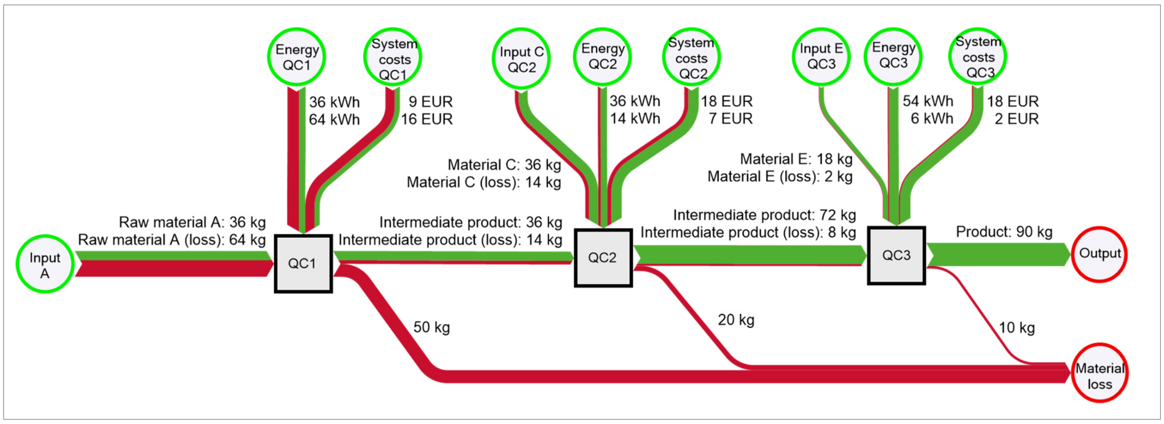


Figure 37: MFCA 2.0 Sankey diagram, all losses are avoided, all losses are avoided—physical flows



The corresponding costs that can be avoided can be determined with the specific cost factors as follows:

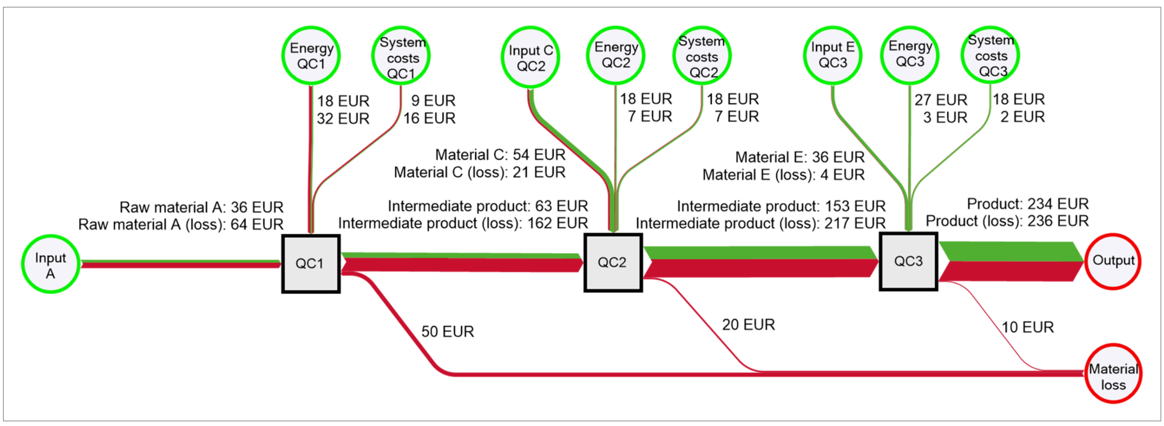
Material costs:	QC1: 64.00 kg·1.00 EUR/kg	= 64.00 EUR
	QC2: 14.00 kg·1.50 EUR/kg	= 21.00 EUR
	QC3: 2.00 kg·2.00 EUR/kg	= 4.00 EUR
		∑ = **89.00 EUR**
Energy costs:	QC1: 64.00 kWh·0.50 EUR/kg	= 32.00 EUR
	QC2: 14.00 kWh·0.50 EUR/kg	= 7.00 EUR
	QC3: 6.00 kWh·0.50 EUR/kg	= 3.00 EUR
		∑ = **42.00 EUR**
System costs:	QC1: 16.00 EUR	= 16.00 EUR
	QC2: 7.00 EUR	= 7.00 EUR
	QC3: 2.00 EUR	= 2.00 EUR
		∑ = **25.00 EUR**

Since all waste flows can be eliminated, 100% of the corresponding waste management costs can be avoided.

Waste management costs:	QC1: 50.00 kg·100%·1.00 EUR/kg	= 50.00 EUR
	QC2: 20.00 kg·100%·1.00 EUR/kg	= 20.00 EUR
	QC3: 10.00 kg·100%·1.00 EUR/kg	= 10.00 EUR
		∑ = **80.00 EUR**

A total of **236.00 EUR** can be saved if the material losses in QC1, QC2 and QC3 can be eliminated completely. Figure 38 shows the monetary flows with all costs allocated to the product following the MFCA 2.0 algorithm. The total saving potential sums up to 236.00 EUR as can be seen from the red share of the product flow. The material loss flows from the material loss place towards the quantity center, respectively, since all costs are carried by the product and the previous division of the costs between product and loss has been repealed with the MFCA 2.0 algorithm.

Figure 38: MFCA 2.0 Sankey diagram, all losses are avoided—monetary flows

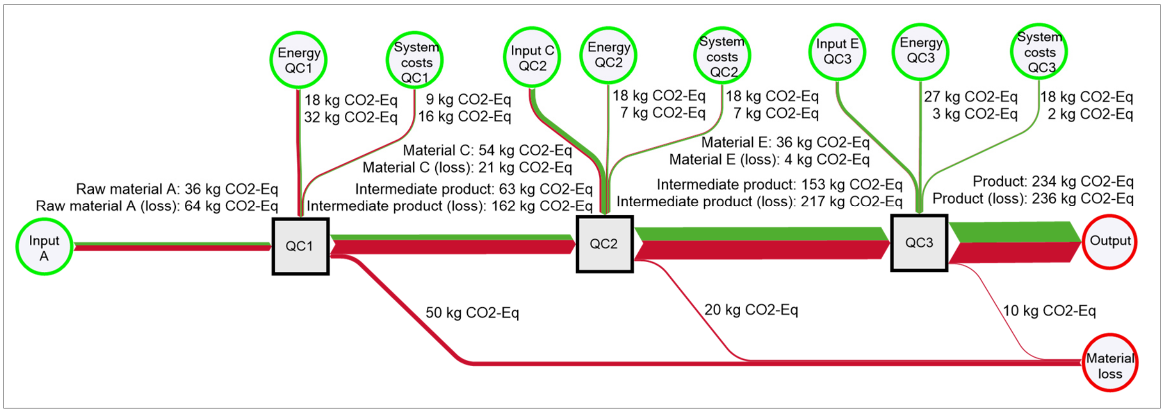


Finally, the GHG emissions that can be avoided as a consequence of the reductions in material losses can be quantified with the help of the specific GHG emission factors:

Material:	QC1: 64.00 kg·1.00 kg CO_2e/kg	= 64.00 kg CO_2e
	QC2: 14.00 kg·1.50 kg CO_2e/kg	= 21.00 kg CO_2e
	QC3: 2.00 kg·2.00 kg CO_2e/kg	= 4.00 kg CO_2e
	$\sum$	= **89.00 kg CO_2e**
Energy:	QC1: 64.00 kWh·0.50 kg CO_2e/kWh	= 32.00 kg CO_2e
	QC2: 14.00 kWh·0.50 kg CO_2e/kWh	= 7.00 kg CO_2e
	QC3: 6.00 kWh·0.50 kg CO_2e/kWh	= 3.00 kg CO_2e
	$\sum$	= **42.00 kg CO_2e**
System costs:	QC1: 16.00 EUR·1.00 kg CO_2e/EUR	= 16.00 kg CO_2e
	QC2: 7.00 EUR·1.00 kg CO_2e/EUR	= 7.00 kg CO_2e
	QC3: 2.00 EUR·1.00 kg CO_2e/EUR	= 2.00 kg CO_2e
	$\sum$	= **25.00 kg CO_2e**
Waste management:	QC1: 50.00 kg·100%·1.00 EUR/kg	= 50.00 kg CO_2e
	QC2: 20.00 kg·100%·1.00 EUR/kg	= 20.00 kg CO_2e
	QC3: 10.00 kg·100%·1.00 EUR/kg	= 10.00 kg CO_2e
	$\sum$	= **80.00 kg CO_2e**

A total of **236.00 kg CO_2e** can be saved if the material losses in QC1, QC2 and QC3 are eliminated completely. Figure 39 summarizes the MFCA 2.0 results for the GHG emissions-based dimension.

Figure 39: MFCA 2.0 Sankey diagram, all losses are avoided—GHG emissions-based flows



4.3.4.8 Case 6: All Three Material Loss Flows Can Be Partly Reduced

Finally, in Case 6, all three material loss flows can be reduced, but only to a certain extent, i.e., they cannot be avoided completely as in Case 5. The loss flows can be reduced as follows:

- The material loss flow in QC1 gets reduced by 20.00 kg or 40% from 50.00 kg to 30.00 kg.
- The material loss flow in QC2 gets reduced by 10.00 kg or 50% from 20.00 kg to 10.00 kg.
- The material loss flow in QC3 gets reduced by 2.00 kg or 20% from 10.00 kg to 8.00 kg.

First of all, the material saving potential for each of the three QCs needs to be quantified with the help of the improvement factors included in equations (4.1), (4.2) and (4.3). Equation (4.3) is required for the inputs of QC1, (4.2) for the inputs of QC2 and (4.1) for the inputs of QC3.

$x = 20\%$
$y = 50\%$
$z = 40\%$

The saving potential for the inputs in QC1 can be quantified with (4.3):

$$saving\ factor\ 3$$
$$= 1 - \left(1 - \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}\right) \cdot \left(1 - \frac{20\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) - 20\ kg \cdot (1 - 50\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)}\right)$$
$$\cdot \left(1 - \frac{50\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) \cdot (1 - \frac{20\ kg \cdot \left(1 - \frac{10\ kg \cdot 100\%}{80\ kg + 20\ kg}\right) - 20\ kg \cdot (1 - 50\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)}) - 50\ kg \cdot (1 - 40\%)}{100\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) \cdot \left(1 - \frac{20\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) - 20\ kg \cdot (1 - 50\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)}\right)}\right)$$

$$saving\ factor\ 3 = 25.8\%$$

The saving potential for the input flows in QC2 can be quantified with (4.2), representing saving factor 2.

$$saving\ factor\ 2$$
$$= 1 - \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)$$
$$\cdot \left(1 - \frac{20\ kg \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right) - 20\ kg \cdot (1 - 50\%)}{(50\ kg + 50\ kg) \cdot \left(1 - \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}\right)}\right)$$

$$saving\ factor\ 2 = 11.6\%$$

The saving potential for raw material C in QC3 can be quantified with (4.1) as follows:

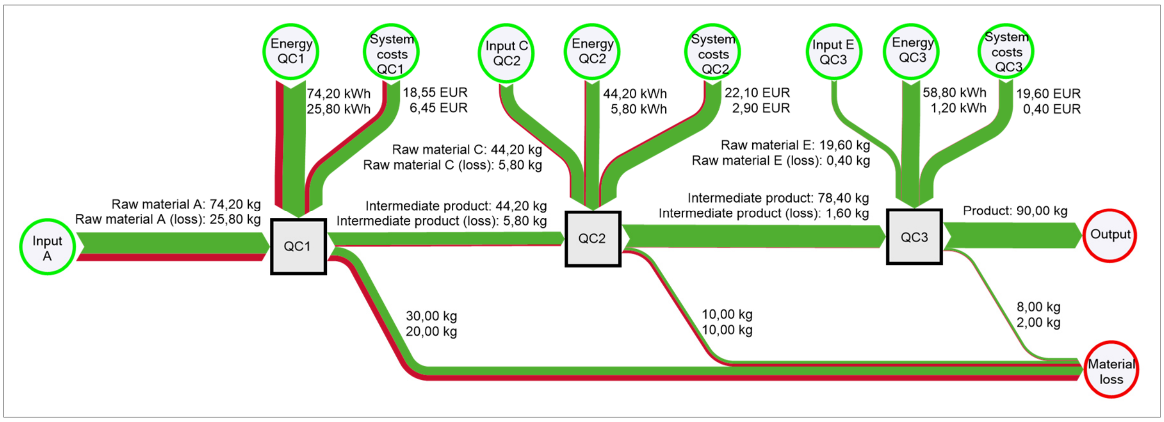
$$saving\ factor\ 1 = \frac{10\ kg \cdot 20\%}{80\ kg + 20\ kg}$$

$$saving\ factor\ 1 = 2.0\%$$

Material:	QC1: 100 kg·25.8%	= 25.80 kg
	QC2: 50 kg·11.6%	= 5.80 kg
	QC3: 20 kg·2.0%	= 0.40 kg
		∑ **= 32.00 kg**
Energy:	QC1: 100.00 kWh·25.8%	= 25.80 kWh
	QC2: 50.00 kWh·11.6%	= 5.80 kWh
	QC3: 60.00 kWh·2.0%	= 1.20 kWh
		∑ **= 32.80 kWh**
System costs:	QC1: 25.00 EUR·25.8%	= 6.45 EUR
	QC2: 25.00 EUR·11.6%	= 2.90 EUR
	QC3: 20.00 EUR·2.0%	= 0.40 EUR
		∑ **= 9.75 EUR**

If the material loss flow in QC1 gets reduced by 20.00 kg (40%), in QC2 by 10.00 kg (50%) and in QC3 by 2.00 kg (20%), a total of **32.00 kg** of materials (25.80 kg of material A, 5.80 kg of material C and 0.40 kg of material E), **32.80 kWh** energy and **9.75 EUR** system costs can be avoided in the system under analysis. Figure 40 includes Sankey diagram and it combines the two scenarios, representing the scenario-based approach of MFCA 2.0. The red shares of the flows indicate the difference between the two scenarios, and this difference represents the saving potentials for this case.

Figure 40: MFCA 2.0 Sankey diagram, material loss reduction in QC1 by 20.00 kg, in QC2 by 10.00 kg and in QC3 by 2.00 kg—physical flows



The monetary saving potentials can be calculated with the help of the prices for the different flows:

Material costs:	QC1: 25.80 kg·1.00 EUR/kg	= 25.80 EUR
	QC2: 5.80 kg·1.50 EUR/kg	= 8.70 EUR
	QC3: 0.40 kg·2.00 EUR/kg	= 0.80 EUR
		∑ = **35.30 EUR**
Energy costs:	QC1: 25.80 kWh·0.50 EUR/kg	= 12.90 EUR
	QC2: 5.80 kWh·0.50 EUR/kg	= 2.90 EUR
	QC3: 1.20 kWh·0.50 EUR/kg	= 0.60 EUR
		∑ = **16.40 EUR**
System costs:	QC1: 6.45 EUR	= 6.45 EUR
	QC2: 2.90 EUR	= 2.90 EUR
	QC3: 0.40 EUR	= 0.40 EUR
		∑ = **9.75 EUR**
Waste management costs:	QC1: 50.00 kg·40%·1.00 EUR/kg	= 20.00 EUR
	QC2: 20.00 kg·50%·1.00 EUR/kg	= 10.00 EUR
	QC3: 10.00 kg·20%·1.00 EUR/kg	= 2.00 EUR
		∑ = **32.00 EUR**

A total of **93.45 EUR** can be saved if the material losses in QC1 are reduced by 40% from 50.00 kg to 30.00 kg, in QC2 by 50% from 20.00 kg to 10.00 kg and in QC3 by 20% from 10.00 kg to 8.00 kg. The calculation of the avoided GHG emissions requires the multiplication of the values with the GHG emission factors:

Material:	QC1: 25.80 kg·1.00 kg CO_2e/kg	= 25.80 kg CO_2e
	QC2: 5.80 kg·1.50 kg CO_2e/kg	= 8.70 kg CO_2e
	QC3: 0.40 kg·2.00 kg CO_2e/kg	= 0.80 kg CO_2e
		∑ = **35.30 kg CO_2e**
Energy costs:	QC1: 25.80 kWh·0.50 kg CO_2e/kg	= 12.90 kg CO_2e
	QC2: 5.80 kWh·0.50 kg CO_2e/kg	= 2.90 kg CO_2e
	QC3: 1.20 kWh·0.50 kg CO_2e/kg	= 0.60 kg CO_2e
		∑ = **16.40 kg CO_2e**
System costs:	QC1: 6.45 EUR·1.00 kg CO_2e/EUR	= 6.45 kg CO_2e
	QC2: 2.90 EUR·1.00 kg CO_2e/EUR	= 2.90 kg CO_2e
	QC3: 0.40 EUR·1.00 kg CO_2e/EUR	= 0.40 kg CO_2e
		∑ **= 9.75 kg CO_2e**
Waste management:	QC1: 50.00 kg·40%·1.00 kg CO_2e/kg	= 20.00 kg CO_2e
	QC2: 20.00 kg·50%·1.00 kg CO_2e/kg	= 10.00 kg CO_2e
	QC3: 10.00 kg·20%·1.00 kg CO_2e/kg	= 2.00 kg CO_2e
		∑ = **32.00 kg CO_2e**

If the material loss in QC1 can be reduced by 40% from 50.00 kg to 30.00 kg, the material loss in QC2 by 50% from 20.00 kg to 10.00 kg and the material loss in QC3 by 20% from 10.00 kg to 8.00 kg, the GHG emissions in the analyzed system can be reduced by **93.45 kg CO_2e**.

4.3.4.9 Juxtaposition of MFCA 1.0 and MFCA 2.0 Including Summary Tables

MFCA 1.0 follows the standard ISO 14051 (ISO, 2011) and gradually allocates costs between the (intermediate) product and loss in the direction of material flow. MFCA 2.0 offers an additional perspective with the calculation of the systemwide saving potentials associated with the reduction of one or multiple material losses. This new perspective oversees to what extent the inputs of the preceding QCs can be reduced as a consequence of the reduction of one or multiple material losses. Thereby, MFCA 2.0 calculates the reductions of the different input flows and adds them up to quantify the total saving potential. This represents an extension to the method following ISO 14051 and adds insofar value to the MFCA results that it does not focus on losses alone, but it adds the perspective of inefficiencies in the form of saving potentials. In other words, an increase in resource efficiency of a production process goes beyond the mere detection and quantification of undesired material losses. The associated saving potentials are highly relevant to build arguments for corporate decision-making because they quantify the effects of these potential improvement measures for the whole system under analysis.

The following three tables contain the MFCA results for the physical, monetary and GHG emissions-based (kg CO_2e) dimension, as shown above. In addition to the values based on ISO 14051, the tables contain the saving potentials based on MFCA 2.0 for Case 1 and Case 5 as well as the minimum values as a result of the difference between the values of the status quo and the maximum saving potentials. These three rows are shaded in grey in each table. The values in the table row *Saving potentials if loss is avoided in the respective QC only* (i.e., Case 1) are composed of one, two or three summands. Since QC1 does not have any preceding QCs, it has one summand only. QC2 has the preceding QC1 and thus has two summands. QC3 has the preceding QCs QC1 and QC2 and therefore has two summands. The row *Saving potential if all losses are avoided* contains the theoretical maximum saving potential presupposing an ideal waste free production process. The three bottom rows summarize the values of the three QCs for the inputs material and energy and system costs. They include the status quo values, the theoretical minimum values that relate to the product and finally the difference of the two values, which represents the maximum saving potential for the case that all losses can be avoided.

Table 9: MFCA matrix including MFCA 2.0 (grey background), physical values

MFCA matrix	QC 1			QC 2			QC 3		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Inputs from previous QC		50	50	12.5	80	80	30		
New inputs in QC	100	100	25.0	50	50	25.0	20	60	20
Total in each QC	100	100	25.0	100	100	37.5	100	140	50
Product of QC	50	50	12.5	80	80	30.0	90	126	45
Material losses (following ISO 14051:2011)	50	50	12.5	20	20	7.5	10	14	5
Total losses	50	50	12.5	70	70	20.0	80	84	25
Saving potential if loss is avoided in the respective QC only	50	50	12.5	20+10 =30	20+10 =30	5+5 =10.0	10+5+2 =17	10+5+6 =21	2.5+2.5+2 =7
Saving potential if all losses are avoided	64	64	16.0	14	14	7.0	2	6	2
Amount if all losses are avoided	36	36	9.0	36	36	18.0	18	54	18
Total amount status quo all flows	170	210	70.0						
Total amounts in the product flow in this process (all QCs)	90	126	45.0						
Total saving potential if all losses are avoided	80	84	25.0						

Table 10: MFCA matrix including MFCA 2.0 (grey background), monetary values

MFCA matrix	QC 1				QC 2				QC 3			
	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs
	EUR	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*
Inputs from previous QC		50	25.0	12.5		100	40.0	30				
New inputs in QC	100	50	25.0		75	25	25.0		40.0	30.0	20	
Total in each QC	100	50	25.0		125	50	37.5		140.0	70.0	50	
Product of QC	50	25	12.5		100	40	30.0		126.0	63.0	45	
Losses (following ISO 14051:2011)	50	25	12.5	50.0	25	10	7.5	20	14.0	7.0	5	10
Total losses	50	25	12.5	50.0	75	35	20.0	70	89.0	42.0	25	80
Saving potential if loss is avoided in the respective QC only	50	25	12.5	50.0	15+20 =35	5+10 =15	5+5 =10.0	20+10 =30	4+7.5+10 =21.5	3+2.5+5 =10.5	2+2.5+2.5 =7	10+2+5 =17
Saving potential if all losses are avoided	64	32	16.0	50.0	21	7	7.0	20	4.0	3.0	2	10
Costs if all losses are avoided	100–64 =36	50–32 =18	25–16 =9.0		75–21 =54	25–7 =18	25–7 =18.0		40–4 =36.0	30–3 =27.0	20–2 =18	
Total costs in this process (all QCs) status quo	100+75+40 =215	50+25+30 =105	25+25+20 =70.0	50+20+10 =80.0								
Total costs, status quo (all QCs)	470											
Total costs if all losses are avoided, i.e., minimum costs (all QCs)	234											
Maximum saving potential	236											

Table 11: MFCA matrix including MFCA 2.0 (grey background), GHG emissions

MFCA matrix	QC1				QC2				QC3			
	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt
	kg CO_2e	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*
Inputs from previous QC					50	25	12.5		100	40	30	
New inputs in QC	100	50	25.0		75	25	25		40	30	20	
Total in each QC	100	50	25.0		125	50	37.5		140	70	50	
Product of QC	50	25	12.5		100	40	30		126	63	45	
Losses (following ISO 14051:2011)	50	25	12.5	50	25	10	7.5	20	14	7	5	10
Total losses	50	25	12.5	50	75	35	20	70	89	42	25	80
Saving potential if loss is avoided in the respective QC only	50	25	12.5	50	15+20 =35	5+10 =15	5+5 =10	20+10 =30	4+7.5+10 =21.5	3+2.5+5 =10.5	2+2.5+2.5 =7	10+2+5 =17
Saving potential if all losses are avoided	64	32	16.0	50	21	7	7	20	4	3	2	10
Emissions if all losses are avoided	100–64 =36	50–32 =18	25–9 =9.0		75–21 =54	25–7 =18	25–7 =18		40–4 =36	30–3 =27	20–2 =18	
Total emissions in this process (all QCs) status quo	100+75+40 =215	50+25+30 =105	25+25+20 =70.0	50+20+10 =80								
Total emissions, status quo (all QCs)	470											
Total emissions if all losses are avoided, i.e., minimum emissions (all QCs)	234											
Maximum saving potential	236											

The differences between the two MFCA approaches can be analyzed based on the tables above. The values in the row *Losses (following ISO 14051:2011)* differ from the values in the row *Saving potential if all losses are avoided*. The latter takes a systemwide perspective, thus shifting the saving potentials in the opposite direction of the material flow, i.e., towards QC1. For example, MFCA 2.0 calculates the saving potentials for QC1 based on the input flows that can be reduced in the system under analysis. If all losses in the system are avoided, the input flows in QC1 can be reduced by 64 kg (column *Material*), 32 kWh (column *Energy*), 16 EUR (column *System costs*) and 50 EUR (column *Waste mgmt costs*) (cf. row *Saving potential if all losses are avoided*). Due to this system-wide view, the saving potentials of QC2 and QC3 are smaller than the values of the row *Losses (following ISO 14051:2011)*. MFCA 1.0, in turn, allocates input flows of the particular QC only based on the mass ratio of the output flows of that particular QC. Thereby, it carries the expenditures towards the losses of the following QCs since it does not oversee the saving potential that is possible in the form of indirect effects on other QCs. However, the two rows correspond with each other regarding their total values for the system under analysis, i.e., QC1, QC2 and QC3. Moreover, the sum values can be found in the row *Total losses* for QC3. The following calculations demonstrate this:

Total losses (QC3):	Material:		89.00 kg
	Energy:		42.00 kWh
	System costs:		25.00 EUR
	Waste management costs:		80.00 EUR

Losses (following ISO 14051:2011):

Material:	50.00 kg+25.00 kg+14.00 kg	= 89.00 kg
Energy:	25.00 kWh+10.00 kWh+7.00 kWh	= 42.00 kWh
System costs:	12.50 EUR+7.50 EUR+5.00 EUR	= 25.00 EUR
Waste management costs:	50.00 EUR+20.00 EUR+10.00 EUR	= 80.00 EUR

Saving potential if all losses are avoided:

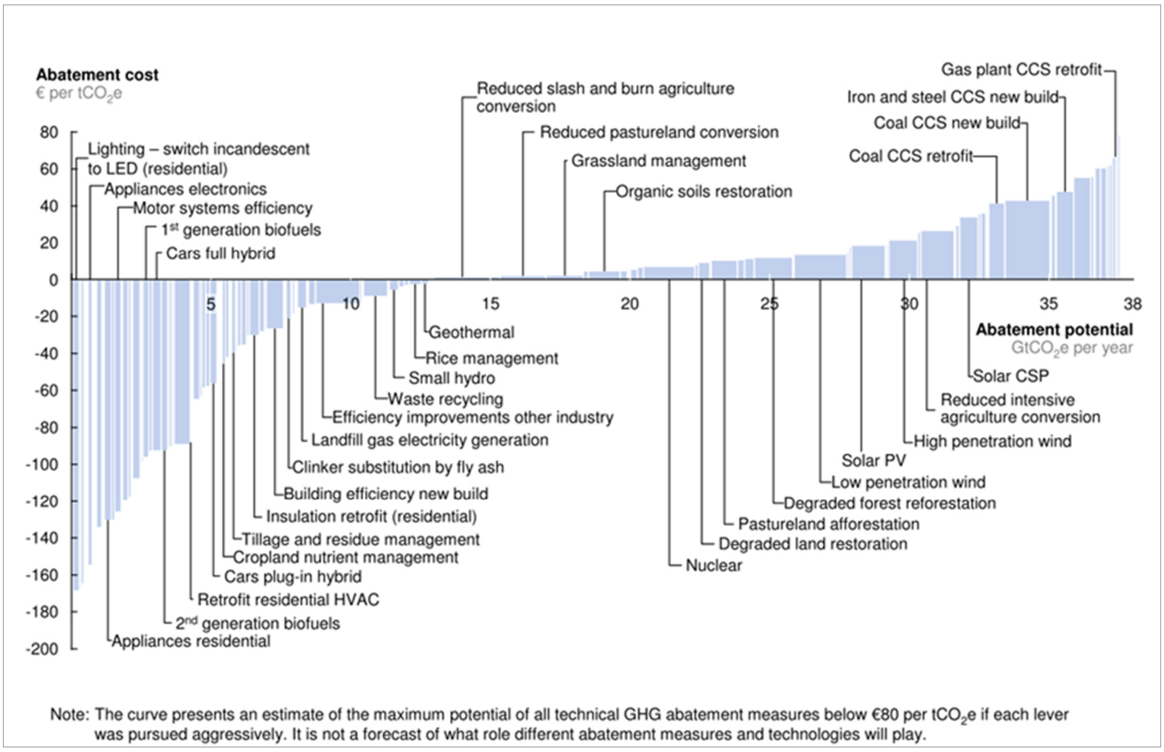
Material:	64.00 kg+21.00 kg+4.00 kg	= 89.00 kg
Energy:	32.00 kWh+7.00 kWh+3.00 kWh	= 42.00 kWh
System costs:	16.00 EUR+7.00 EUR+2.00 EUR	= 25.00 EUR
Waste management costs:	50.00 EUR+20.00 EUR+10.00 EUR	= 80.00 EUR

This example demonstrates how MFCA 2.0 enriches the method's results with information on saving potentials in physical, monetary and environmental measuring units. The saving potentials are related to material loss reductions, and a consequence thereof are the minimum efforts—in physical, monetary and environmental units as well—under the condition that all material losses can be avoided. Additionally, any other case of a loss flow reduction can be calculated, as shown with the various exemplary cases above. This offers a significant and practice-oriented extension of the method. In summary, MFCA 2.0 provides a valuable addition to the method and empowers its users such as a manufacturing company to evaluate different resource efficiency measures.

4.3.4.10 Economic-Ecological Efficiency of MFCA 2.0

In order to combine the ecological and economic dimension, certain indicators can be determined. One of them is the abatement cost, which McKinsey coined and published an *abatement curve* for the US for the first time in 2007 and developed it further into a *global GHG abatement cost curve* (McKinsey & Company, 2009, 2010). Figure 41 shows the abatement cost curve v2.1. Starting on the left, it can be seen that there are measures which have a low annual abatement potential, but due to the low investment cost of the measure, the abatement cost per t CO_2e is negative, i.e., this measure is worthwhile from an economic point of view within the time frame of one year since it causes a cost reduction. Around 12 Gt CO_2e per year, the abatement cost in EUR per t CO_2e measures that are included in the analysis become positive, i.e., the measure causes additional costs within the one-year time frame. This means that with the listed measures including *Geothermal*, 12 Gt CO_2e are avoided and that costs can be reduced at the same time. The amount of additional costs increases along the x-axis until the measure with the highest relative abatement cost (80 EUR/t CO_2e in the diagram) has been reached.

Figure 41: Global GHG abatement cost curve beyond BAU—2030 (McKinsey & Company, 2010, p. 8)



Despite the following critique, McKinsey & Company's work should be acknowledged for the following remark:

> The objective was to provide the first globally consistent dataset as a starting point for global discussions about how to reduce GHG emissions, showing the relative importance of different sectors, regions, and abatement measures, and providing a factual basis on the cost of reducing emissions. (McKinsey & Company, 2009, p. 20)

The idea to calculate abatement costs as a result of emissions and GHG emission abatement measures and its implementation in a study represent an important step towards the combination of the ecological and economic dimension. The key points of criticism regarding McKinsey & Company's (2010) work will be summarized in the following paragraph.

First, there are methodological problems since the abatement cost curve is limited to GHG emissions as an indicator for climate change (Ekins et al., 2011). Second, the calculations represent static calculations for a one-year time period, but further assumptions are not clearly evident (Ekins et al., 2011). Third, Ekins et al. (2011) explain, the abatement cost curve is not able to include qualitative aspects like interdependencies, synergies and conflicts as well as implementation barriers and uncertainty factors. In theory, the impact, i.e., the abatement potential, of multiple measures being implemented at the same time could be modeled and their combined effect could be calculated. This question is similar to the saving potential that MFCA 2.0 strives to quantify when combining multiple loss-reducing measures (cf. Subsection 4.3.4). Finally, despite the constructive critique, the authors express support for the calculation and the use of the abatement cost curve, including the following recommendations. The calculation period should be extended (currently one year) and additionally, they recommend extending the results with the immanent complexity, thus making the results more transparent and providing a view beyond the costs of the different measures (Ekins et al., 2011).

In general, the calculation of the abatement potential and a carbon price—albeit requiring additional policies—are important steps because they offer structure in political debates. This is in line with the publication by McKinsey & Company (2010) and Ekins et al.'s (2011) critical evaluation. The concept of the abatement cost curve was once developed with a focus on the political realm, and it was then used by many organizations, industries and companies because it provides guidance to decision-makers (McKinsey & Company, 2017). An abatement cost curve can help to prioritize different options for action that specifically address climate change (McKinsey & Company, 2017). Nevertheless, just like the political application of the abatement cost curve requires additional policies, the application in an organizational context requires decisions and subsequent action. It is not an end in itself, but it remains a stepping stone to climate protection.

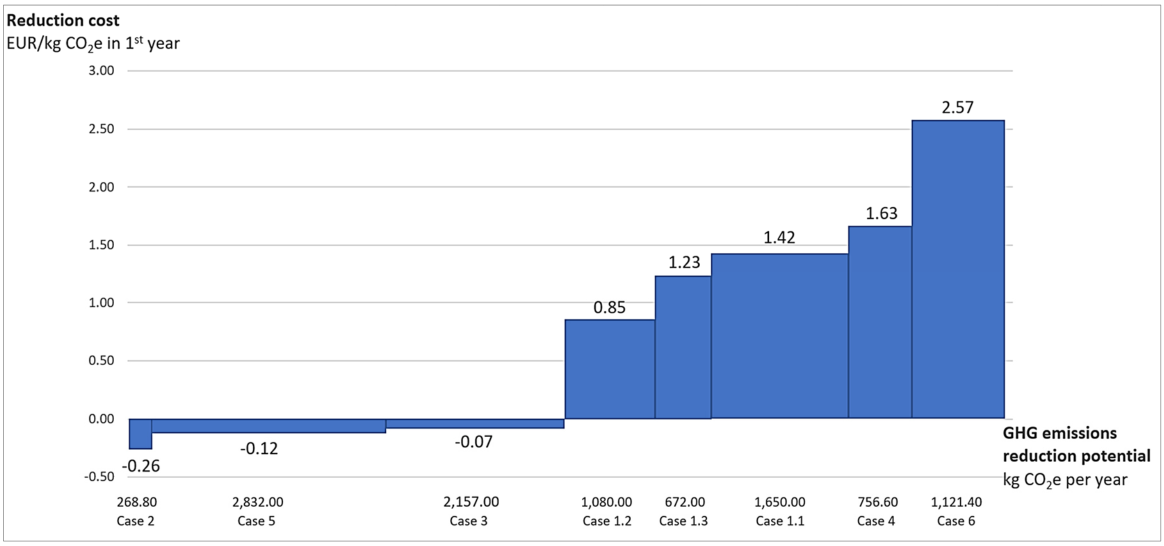
The concept of the abatement cost curve will now be transferred to MFCA 2.0 from a company perspective, leading to the following results. The figures of Subsection 4.3.4 refer to a one-month period, i.e., the emissions saving potentials were multiplied with 12 to calculate the annual reduction potential. When calculating the case-specific reduction cost, the annual monetary cost saving potential due to the reduced physical flows—which in these fictitious cases equals the GHG emissions saving potentials—needs to be subtracted from the investment cost. Within the period of one year, the initial investment cost can be reduced by the monthly cost reduction potential multiplied with 12 to scale it up to 12 months or one year. The result can then be divided by the annual GHG emissions reduction potential. Table 12 includes the calculation results and Figure 42 includes the GHG emissions reduction cost curve for the different cases in Subsection 4.3.4. Just like the figures in the MFCA model, the figures for the investment costs are fictitious as well. For Case 2 (the material loss of 10.00 kg in QC3 can be reduced by 40%), the reduction cost is the lowest with –0.26 EUR/kg CO_2e per year, meaning that the measure is financially profitable within the first year already. The investment cost is 200 EUR, as can be read off from Table 12. The annual GHG emission reduction potential of this case is 268.80 kg CO_2e. Case 6 has the highest relative reduction cost with 2.57 EUR/kg CO_2e and—like Case 1—the highest investment cost with 4,000 EUR, respectively. Case 5 has the highest GHG emissions reduction potential with 2,832.00 kg CO_2e. Furthermore, Cases 2, 3 and 5 are the most desirable from and economic-ecological point of view because their reduction cost is negative. This means that the monetary saving potential of the cases within the first year after the implementation of the measure is larger than the initial investment cost of the measure, respectively.

The results in Table 12 and the underlying assumptions and conditions of the respective case (cf. the respective case in Subsection 4.3.4) represent a sound basis for a discussion of the different optional measures. Such a discussion may also dive deep into different dimensions such as the different cost components (material costs, energy costs, system costs) and the localization of GHG emissions along the process chain or the different quantity centers. In summary, MFCA 2.0 provides highly decision-relevant information and thus supports economic-ecological management discussions and decisions.

Table 12: Overview of economic-ecological efficiency of the cases in Subsection 4.3.4

	Case 1.1	Case 1.2	Case 1.3	Case 2	Case 3	Case 4	Case 5	Case 6
Reduction potential *kg CO_2e per year*	1,650.00	1,080.00	672.00	268.80	2,157.00	761.40	2,832.00	1,121.40
Investment cost *EUR*	4,000	2,000	1,500	200	2,000	2,000	2,500	4,000
Reduction cost *EUR/kg CO2e*	1.42	0.85	1.23	–0.26	–0.07	1.63	–0.12	2.57

Figure 42: GHG emissions reduction cost curve for the cases in Subsection 4.3.3 (Own illustration)



Besides the GHG emissions reduction potential and the reduction cost, the following indicators can be decision-relevant because a company may have certain requirements or standards regarding these indicators such as a maximum total (annual) investment budget or a maximum payback period:

- Investment cost
- Payback period
- Return on investment
- Production downtime during implementation of measure

Depending on the interests of the persons involved, the calculation and analysis of additional cases such as the combination of different cases can be required. To do so, the relevant measures, i.e., the material loss reductions included in the cases, should be modeled and calculated with the scenario-based approach of MFCA 2.0. In this way, the economic-ecological efficiency of different measures and combinations thereof can be assessed and compared, enabling informed decisions. This is an important indicator for management decisions resulting from an MFCA analysis that has not existed so far. As has been explained above, these figures alone are not sufficient for a well-informed decision since they have multiple limitations. However, if the assumptions are openly and clearly stated and qualitative aspects like implementation barriers or interdependencies are included in the discussions and decisions, the diagram of the abatement cost curve will be a useful tool to visualize the results and open the floor for discussions.

4.3.5 Evaluation of System-Internal Material Loops With MFCA 2.0

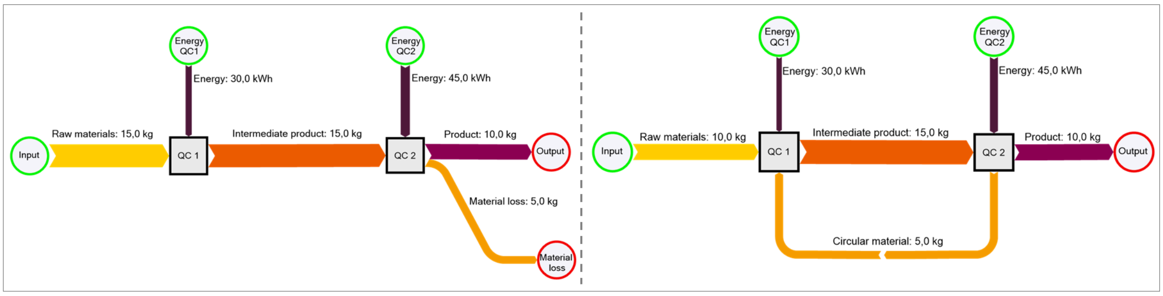
The new algorithm behind MFCA 2.0 allows the modeling of system-internal loops as well. It enables the quantification of the additional or reduced efforts related to the loops in physical, monetary and GHG emissions units. Internal loops can avoid a loss flow in a system, and the production system might therefore appear as efficient at first sight. Applying the scenario-based approach, the status quo of the production system and the improved scenario—with or without the material loop, depending on the status quo and the specific case—are compared. Based on the difference between the two states, saving potentials can then be quantified. Two different cases will be illustrated. In this example, waste management costs and emission factors apply. The following QC-specific energy demand, cost and emission factors apply:

- Energy demand QC1: 2.00 kWh/kg
- Energy demand QC1: 3.00 kWh/kg
- Energy costs: 0.50 EUR/kWh
- Material costs: 1.00 EUR/kg
- Waste management costs: 1.50 EUR/kg
- Energy emission factor: 0.50 kg CO_2e/kWh
- Material emission factor: 1.00 kg CO_2e/kWh
- Waste management emission factor: 1.50 kg CO_2e/kWh

4.3.5.1 Case 1: Is the Introduction of a Material Loop Useful?

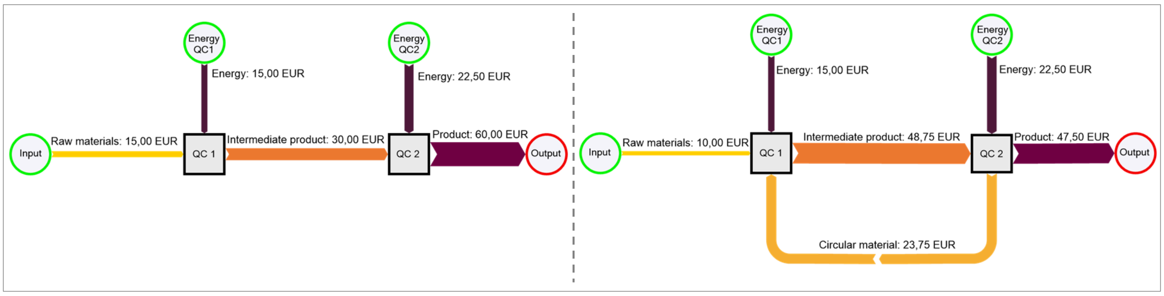
Case 1 is based on the status quo of a model that has a material loss flow in QC2. The improved scenario introduces a material loop that turns the material loss flow into an input flow feeding QC1. Figure 43 shows the Sankey diagram of the status quo with the material loss flow in QC2 and the improved scenario with a material loop, respectively. In this case, the material loop is considered a potential improvement that needs to be analyzed. The scenario-based approach of MFCA 2.0 compares the difference between the two scenarios and thus quantifies the saving potential. The saving potential can be derived from the values of the three input flows that the only input flow changing its value compared to the status quo is the raw materials flow entering QC1. The energy demand stays constant for QC1 (30.0 kWh) and QC2 (45.0 kWh), respectively. Consequently, in this case, the saving potential is a result of the difference of the raw material entering QC1. It is 5.0 kg smaller in the improved scenario (10.0 kg) than in the status quo (15.0 kg). In summary, the physical saving potential related to the introduction of a material loop is 5.0 kg.

Figure 43: Sankey diagrams of an MFCA model, left: status quo, right: improved scenario with material loop—physical flows



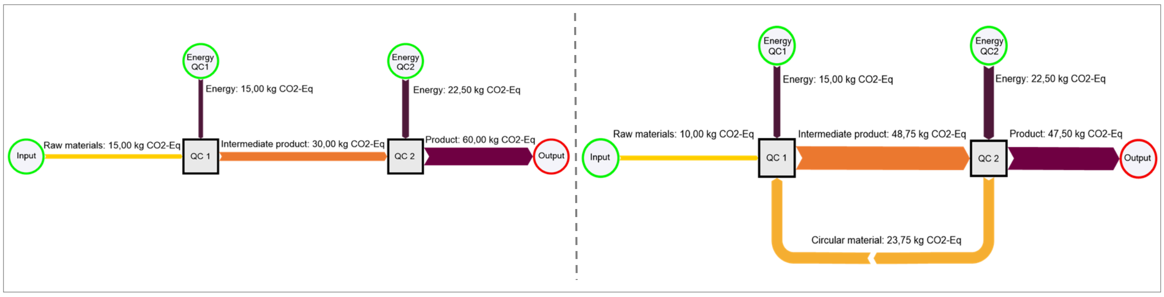
Looking at the monetary dimension, Figure 44 provides the Sankey diagrams of the two scenarios including the values of the monetary flows. Following the saving potential of 5.0 kg raw materials, this physical value needs to be multiplied with the cost factor (1.00 EUR/kg), resulting in 5.00 EUR. The waste management cost of 1.50 EUR/kg, i.e., 7.50 EUR, needs to be added, summing up to 12.50 EUR. This value can be verified with the difference of the two product flows (60.00 EUR–47.50 EUR = 12.50 EUR).

Figure 44: Sankey diagrams of an MFCA model, left: status quo, right: improved scenario with material loop—monetary flows



Following the algorithm of the monetary dimension, the saving potential in kg CO_2e can be quantified with the emission factors for the different input flows. The corresponding flows are depicted in Figure 45. The saving potential amounts to 12.50 kg CO_2e and it is the result of the saving potential of raw materials and the elimination of the emissions related to waste management. Following the monetary dimension, the introduction of a material loop will reduce the GHG emissions related to the process under analysis since potential waste management efforts will be avoided.

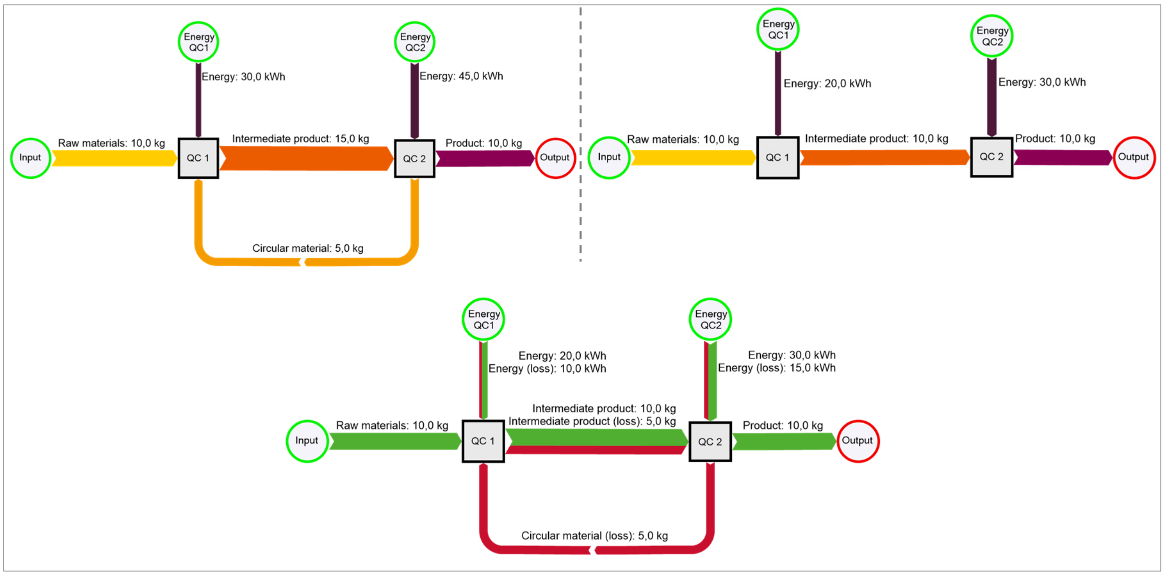
Figure 45: Sankey diagrams, left: status quo, right: improved scenario with material loop—GHG emissions-based flows



4.3.5.2 Case 2: Is an Existing Material Loop Useful?

This case focuses on the question whether an existing material loop is useful or whether it should be eliminated. Figure 46 shows an exemplary model with a material loop turning 5.0 kg of the output of QC2 into an input flow into QC1 (top left, status quo). At the top right, the ideal scenario without the material loop is depicted. In this ideal scenario—all material inputs lead immediately to the product flow, i.e., 10.0 kg input in QC1 are turned into 10.0 kg intermediate product and then into 10.0 kg product without any other output flows. The MFCA 2.0 approach is illustrated below the two diagrams. It shows the saving potentials marked in red in the flows, respectively. In this case, the material loop is completely red because it is not necessary in order to maintain the product flow and can be saved. Therefore, it does not appear in the ideal scenario (bottom) anymore. With the elimination of the material loop and the consequent reduction of the material flow quantity between the two quantity centers, the energy demand of the system under analysis reduces as well. As a result, 10.0 kWh (QC 1) and 15.0 kWh (QC 2), i.e., 25.0 kWh in total, can be saved. There is no immediate material loss in the system since the circular material is led back into the process. In summary, the material loop conceals energy saving potentials that can be realized through the elimination of the material loop.

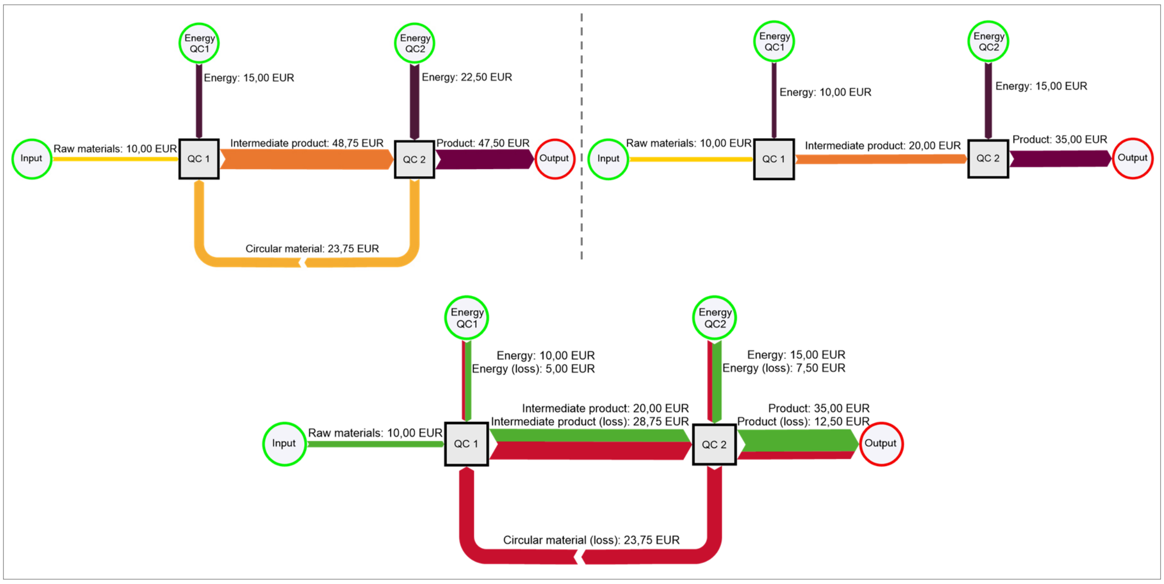
Figure 46: Sankey diagrams showing the status quo with material loop (top left), the improved scenario (top right) and the MFCA 2.0 diagram (bottom)—physical flows



Note. The MFCA 2.0 Sankey diagram (bottom) results from the differences of the two scenarios. The proportion of flows in the system that can be saved with the same production volume is shown in red. Linear relationships are assumed.

The monetary dimension is depicted in the following Figure 47. The saving potentials are marked in red, respectively. The intermediate product carries 28.75 EUR of monetary value, and the circular flow carries 23.75 EUR. The product flow discloses the saving potential related to the elimination of the material loop. It amounts to 12.50 EUR and is based on the additional energy demand of the material loop.

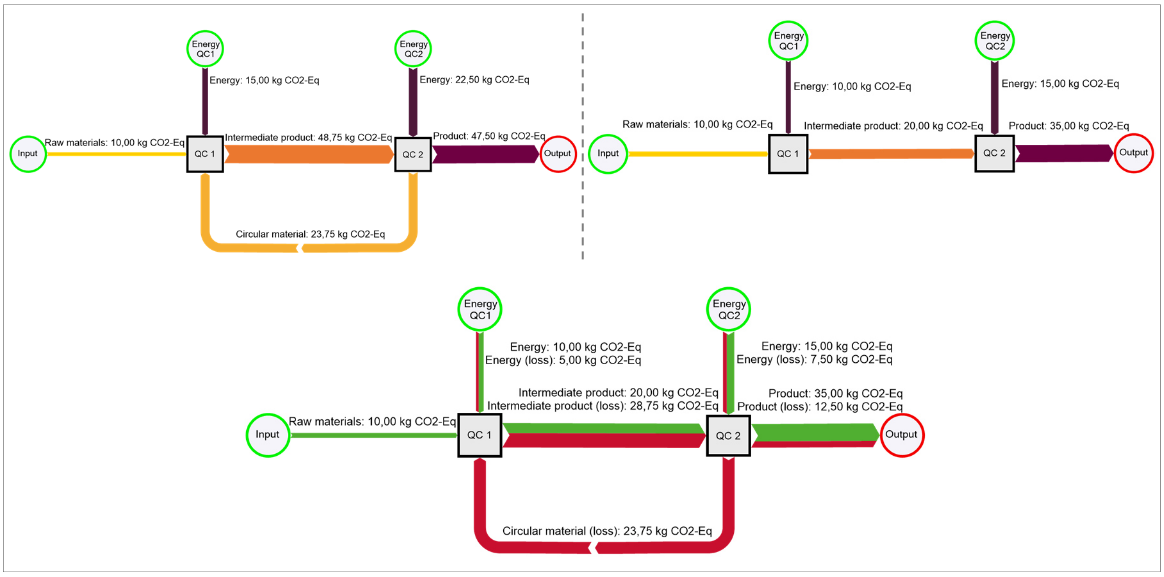
Figure 47: Sankey diagrams showing the status quo with material loop (top left), the improved scenario (top right) and the MFCA 2.0 diagram (bottom)—monetary flows



Note. Sankey diagrams status quo (top left), improved scenario (top right), MFCA 2.0 (bottom) resulting from the differences of the two scenarios. The proportion of flows in the system that can be saved with the same production volume is shown in red (bottom). Constant prices per unit are assumed.

Figure 48 illustrates the flows from an environmental perspective in kg CO_2e. As can be seen, the reduction in energy demand due to the elimination of the material loop enables reduction potentials of GHG emissions of 12.50 kg CO_2e.

Figure 48: Sankey diagrams, status quo with material loop (top left), the improved scenario (top right) and MFCA 2.0 diagram (bottom)—GHG emissions-based flows



Note. The proportion of flows in the system that can be saved with the same production volume is shown in red (bottom). Constant GHG emissions per unit are assumed.

The following tables summarize these results and include the values of the models in matrix form. Table 13 includes the physical MFCA matrix, Table 14 contains the corresponding monetary values and Table 15 includes the GHG emissions related to the material loop example. The rows *Circular input flow* and *Circular output flow* include the values related to loop, and the row *Saving potential if material loop is avoided* includes the amounts that could be avoided, respectively. Although there is no immediate material loss, the recirculation of the 5.0 kg leaving QC2 and reentering the production process in QC1 requires additional energy of 25.0 kWh (10.0 kWh+15.0 kWh) or 12.50 EUR, being tantamount with the saving potential related to the elimination of the material loop. The elimination of the material loop does not reduce the material input flow in QC2, but it reduces the following material flows and consequently also the energy demand of the QC2.

Table 13: MFCA 2.0 matrix of the material loop example, physical values

MFCA matrix	QC 1		QC 2	
	Material	Energy	Material	Energy
	kg	*kWh*	*kg*	*kWh*
Inputs from previous QC		15	30	
New inputs in QC	10	30	0	45
Circular input flow	5	10	0	0
Total in each QC	15	40	15	75
Output flow towards product	15	40	10	50
Circular output flow	0	0	5	25
Saving potential if material loop is avoided	0	10	0	15
Amount if all losses are avoided	10	20	0	30
Total amount status quo (all QCs)	10	75		
Total saving potential if material loop is avoided	0	25		

Table 14: MFCA 2.0 matrix of the material loop example, monetary values

MFCA matrix	QC 1		QC 2	
	Material costs	Energy costs	Material costs	Energy costs
	EUR	*EUR*	*EUR*	*EUR*
Inputs from previous QC		15	15.0	
New inputs in QC	10	15		22.5
Circular input flow	5	5		
Total in each QC	15	20	15	37.5
Output flow towards product	15	20	10	25.0
Circular output flow			5	12.5
Saving potential if material loop is avoided	0	5		7.5
Amount if all losses are avoided	10	10		15.0
Total costs status quo (all QCs)	47.5			
Total saving potential if material loop is avoided	12.5			

Table 15: MFCA 2.0 matrix of the material loop example, GHG emissions

MFCA matrix	QC 1		QC 2	
	Material	Energy	Material	Energy
	kg CO_2e	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*
Inputs from previous QC		15	15.0	
New inputs in QC	10	15		22.5
Circular input flow	5	5		
Total in each QC	15	20	15	37.5
Output flow towards product	15	20	10	25.0
Circular output flow			5	12.5
Saving potential if material loop is avoided	0	5		7.5
Amount if all losses are avoided	10	10		15.0
Total emissions status quo (all QCs)	47.5			
Total saving potential if material loop is avoided	12.5			

4.3.5.3 Conclusion: System-Internal Material Loops in MFCA 2.0

System-internal material loops can be evaluated with the scenario-based algorithms of MFCA 2.0. Whether a loop is useful or not depends on the specific case, i.e., what the alternative scenario looks like. The introduction of a material loop may appear to be a useful improvement measure compared to an existing material loss flow. It can avoid the occurrence of a material loss flow and the management thereof including waste management costs, which will reduce the overall material demand under certain conditions. However, this needs to be examined for a specific production process since, for example, additional energy demand related to the circulation aside from the existing QCs may occur.

Taking a different perspective, an existing production system may seem resource efficient at first sight because there are no immediate material losses. Therefore, internal material loops increase the material efficiency of a process. However, they still require energy, monetary and ecological efforts, and the avoidance of the material flow forming the loop or a loss flow would be the preferred option. Moreover, there may be hidden efforts required to keep the material in the loop apart from the two QCs. Such efforts can, for example, be additional energy, manpower or the wear and tear of the production facility through the additional material passage. If the material loop can be reduced or even eliminated, the efforts will be reduced as well, just like the energy demand in the example. This, in turn, leads to reductions of the related costs and environmental emissions. These effects need to be quantified for a specific case, respectively. Based on the two exemplary cases above, the following statements can be derived.

1. The introduction of a material loop that replaces an existing material loss flow may be useful from a resource-based, monetary and environmental perspective. In the example, the input flow of new raw materials can be reduced by 5.00 kg with the material loop. This represents 12.50 EUR and 12.50 kg CO_2e, including waste management efforts, respectively. The energy demand remains unchanged in the example. However, depending on the requirements of the material loop, energy demand and other efforts could increase, which need to be quantified and weighed for each specific case.
2. The inverse conclusion of the previous statement is that an existing material loop may be more useful from a resource-based, monetary and environmental point of view than the acceptance of a material loss flow and the additional efforts that are related to it. As pointed out above, this is subject to the conditions of the individual case.
3. An existing material loop requires additional energy in comparison to an ideal scenario in which no flows exist that do not flow into the final product. Additional energy is required to maintain the flow of the increased amount of material in the loop. In the example, 25 kWh are required additionally compared to the elimination of the output flow, representing a saving potential of 12.50 EUR or 12.50 kg CO_2e.

Following the 3R principle *reduce, reuse, recycle*, internal loops should be a measure after material losses have been reduced. However, depending on the case-based production conditions and action alternatives, a material loop can be a reasonable measure—after the thorough search for loss-reducing alternative measures. The aim that should be aspired is a production system in which the throughput of material and energy demand have been minimized for the production of a constant amount of product (Viere et al., 2010).

4.3.6 Non-Linear Example With Three Quantity Centers

After the illustration of the scenario-based algorithms with linear MFCA models, this subsection will focus on a non-linear example. The material flow model of Subsection 4.3.4 will serve as a starting point. To explain the MFCA 2.0 approach in a comprehensible way, energy demand will be defined with non-linear functions in this subsection. All other model characteristics remain unchanged. In the example, energy demand depends on the material input flow *m* in each QC. It can be defined with these three formulas:

m: mass of the material input flow in the QC

$$\text{Energy demand}_{\text{QC1}} = \frac{0.1\ \text{kWh} \cdot m^2}{\text{kg}^2}$$

$$\text{Energy demand}_{\text{QC2}} = \frac{0.2\ \text{kWh} \cdot m^2}{\text{kg}^2} + 500\ \text{kWh}$$

$$\text{Energy demand}_{\text{QC3}} = 1.000\ \text{kWh} - 300\ \text{kWh} \cdot \text{e}^{-0.005 \cdot m/\text{kg}}$$

The mass-dependent factors for the system costs remain unchanged:

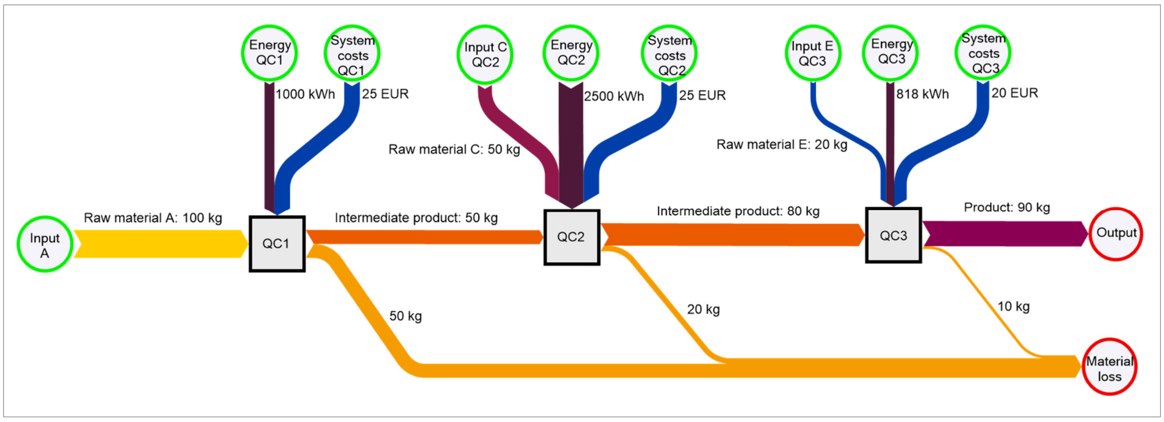
- QC1: 0.25 EUR/kg
- QC2: 0.25 EUR/kg
- QC3: 0.20 EUR/kg

Table 16 contains the MFCA results for the physical dimension based on the standard ISO 14051 (ISO, 2011). Figure 49 shows the corresponding Sankey diagram.

Table 16: MFCA matrix status quo, non-linear energy demand, physical values

MFCA matrix	QC1			QC2			QC3		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Inputs from previous QC				50	500	12.5	80	2,400.00	30
New inputs in QC	100	1,000	25.0	50	2,500	25.0	20	818.04	20
Total in each QC	100	1,000	25.0	100	3,000	37.5	100	3,218.04	50
Product of QC	50	500	12.5	80	2,400	30.0	90	2,896.24	45
Material losses (following ISO 14051:2011)	50	500	12.5	20	600	7.5	10	321.80	5
Total losses	50	500	12.5	70	1,100	20.0	80	1,421.80	25
Total amounts in the product of this process (all QCs)	90	2,896.24	45						

Figure 49: Sankey diagram of the MFCA model with non-linear energy demand, status quo—physical flows



Having defined the status quo scenario, the improved scenario needs to be defined next. In the example, the material loss flow of 10.00 kg in QC3 shall be reduced by 80% to 2.00 kg. Since energy demand and system costs depend on the material flows, the material-based saving potential needs to be quantified first with (4.1) to calculate saving factor 1:

$$saving\ factor\ 1 = \frac{10.00\ kg \cdot 80\%}{80.00\ kg + 20.00\ kg}$$

$$saving\ factor\ 1 = 8\%$$

Since QC1 and QC2 are located before QC3 with regard to the direction of the material flow and only one loss flow gets improved, the saving factor can be applied to all input flows of the QCs, respectively. The following calculations result in the saving potentials:

Material saving potential:	QC1: 100.00 kg·8%	= 8.00 kg
	QC2: 50.00 kg·8%	= 4.00 kg
	QC3: 20.00 kg·8%	= 1.60 kg
		∑ = **13.60 kg**

The quantification of the material saving potentials for the different QCs allows the calculation of the new material input flows for the three QCs, respectively:

Improved material flows:	QC1: 100.00 kg – 8.00 kg	= 92.00 kg
	QC2: 50.00 kg – 4.00 kg	= 46.00 kg
	QC3: 20.00 kg – 1.60 kg	= 18.40 kg

These improved material flows can be used to define the other material flows in the system under analysis based on the condition that the ratios between the different material input flows are constant. Starting with QC3, the product flow of 90 kg remains constant. The material loss flow in QC3 gets reduced to 2 kg. The two input flows of QC3 can now be quantified based on their ratio in the status quo scenario as follows. For the sake of completeness, the flows that were calculated above already were calculated again. This serves as double check and shows that there are different calculation approaches leading to the same results.

$$\text{material flow}_{new\ inputs\ in\ QC3} = \frac{(90\text{ kg} + 2\text{ kg}) \cdot 20\text{ kg}}{80\text{ kg} + 20\text{ kg}} = 18.4\text{ kg}$$

$$\text{material flow}_{inputs\ from\ previous\ QC2} = \frac{(90\text{ kg} + 2\text{ kg}) \cdot 80\text{ kg}}{80\text{ kg} + 20\text{ kg}} = 73.6\text{ kg}$$

Next, the material flow values for QC2 can be calculated:

$$\text{material flow}_{loss\ flow\ QC2} = \frac{73.6\text{ kg} \cdot 20\text{ kg}}{80\text{ kg}} = 18.4\text{ kg}$$

$$\text{material flow}_{new\ inputs\ in\ QC2} = \frac{(18.4\text{ kg} + 73.6\text{ kg}) \cdot 50\text{ kg}}{50\text{ kg} + 50\text{ kg}} = 46\text{ kg}$$

$$\text{material flow}_{inputs\ from\ previous\ QC1} = \frac{(18.4\text{ kg}+73.6\text{ kg}) \cdot 50\text{ kg}}{50\text{ kg}+50\text{ kg}} = 46\text{ kg}$$

Finally, the two material flow values for QC1 follow the same algorithm:

$$\text{material flow}_{loss\ flow\ QC3} = \frac{46\ \text{kg} \cdot 50\ \text{kg}}{50\ \text{kg}} = 46\ \text{kg}$$

$$\text{material flow}_{input\ in\ QC3} = \frac{46\ \text{kg} \cdot 100\ \text{kg}}{50\ \text{kg}} = 92\ \text{kg}$$

Now, the MFCA matrix with the physical values in Table 17 can be filled with the material flow values for the improved scenario. Moreover, the corresponding energy and system costs can be added.

Improved energy flows: QC1: $\text{Energy demand}_{\text{QC1}} = \frac{0.1\ \text{kWh}\cdot(92\ \text{kg})^2}{\text{kg}^2} = 846.40\ \text{kWh}$

QC2: $\text{Energy demand}_{\text{QC2}} = \frac{0.2\ \text{kWh}\cdot(92\ \text{kg})^2}{\text{kg}^2} + 500\ \text{kWh} = 2{,}192.80\ \text{kWh}$

QC3: $\text{Energy demand}_{\text{QC3}} = 1.000\ \text{kWh} - 300\ \text{kWh} \cdot \text{e}^{-0.005 \cdot \frac{92\ \text{kg}}{\text{kg}}} = 810.61\ \text{kWh}$

Improved system costs: QC1: $\text{System costs}_{\text{QC1}} = \frac{0.25\ \text{EUR}}{\text{kg}} \cdot 92\ \text{kg} = 23.0\ \text{EUR}$

QC2: $\text{System costs}_{\text{QC2}} = \frac{0.25\ \text{EUR}}{\text{kg}} \cdot 92\ \text{kg} = 23.0\ \text{EUR}$

QC3: $\text{System costs}_{\text{QC3}} = \frac{0.2\ \text{EUR}}{\text{kg}} \cdot 92\ \text{kg} = 18.4\ \text{EUR}$

Table 17 includes the different flows of the improved scenario. It also contains the MFCA 1.0 approach following the standard ISO 14051 (ISO, 2011).

Table 17: MFCA matrix for improved scenario, non-linear energy demand, physical values

MFCA matrix	QC1			QC2			QC3		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Inputs from previous QC				46.0	423.20	11.5	73.6	2,092.80	27.6
New inputs in QC	92	846.40	23.0	46.0	2,192.80	23.0	18.4	810.61	18.4
Total in each QC	92	846.40	23.0	92.0	2,616.00	34.5	92.0	2,903.41	46.0
Product of QC	46	423.20	11.5	73.6	2,092.80	27.6	90.0	2,840.29	45.0
Material losses (following ISO 14051:2011)	46	423.20	11.5	18.4	523.20	6.9	2.0	63.12	1.0
Total losses	46	423.20	11.5	64.4	946.40	18.4	66.4	1,009.52	19.4
Total amounts in the product of this process (all QCs)	90	2,840.29	45.0						

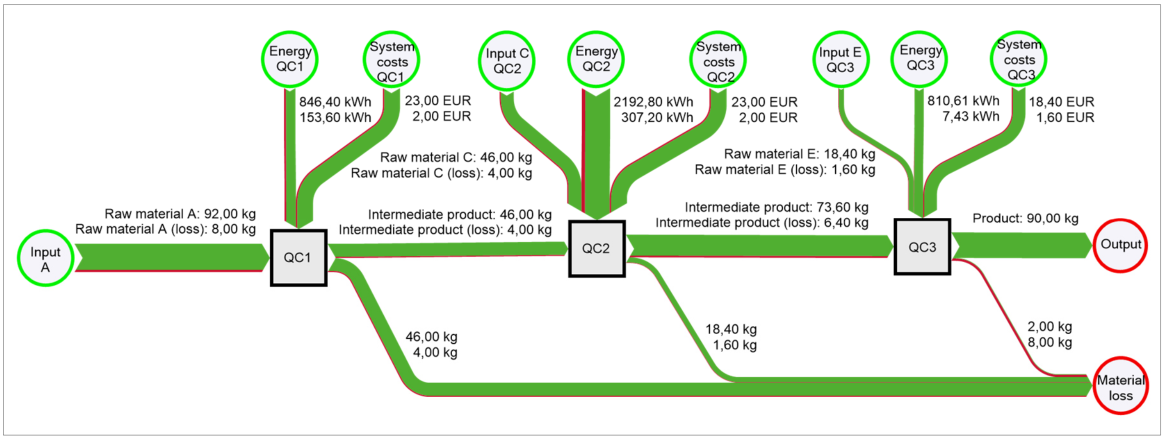
In Table 18, the physical saving potentials for energy and system costs were quantified based on the non-linear energy demand following the scenario-based approach:

Table 18: Calculation of physical saving potential, non-linear energy demand

New inputs in QC	QC1			QC2			QC3			Total		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Status quo scenario	100	1,000.00	25	50	2,500.00	25	20.0	818.04	20.0	170.0	4,318.04	70.0
Improved scenario	92	846.40	23	46	2,192.80	23	18.4	810.61	18.4	156.4	3,849.81	64.4
Saving potential	8	153.60	2	4	307.20	2	1.6	7.43	1.6	13.6	468.23	5.6

If the material loss flow in QC3 can be reduced by 80% from 10.0 kg to 8.0 kg, 13.6 kg of materials (8.0 kg of material A, 4.0 kg of material C and 1.6 kg of material E), 468.23 kWh energy and 5.6 EUR system costs can be saved in the system under analysis. The following Figure 50 includes the physical MFCA 2.0 flow model. The difference between the respective flow values represents the saving potential for this specific case. These saving potentials are marked in red.

Figure 50: MFCA 2.0 Sankey diagram, material loss in QC3 is reduced by 8.0 kg, non-linear energy demand—physical flows



In order to quantify the monetary saving potentials, the following prices were used. They are the same as for the previous cases—except for the energy price, which includes a basic fee and then follows a graduated pricing mechanism, meaning that, for example, the first three thousand kWh cost 0.40 EUR/kWh, whereas the next one thousand kWh cost 0.30 EUR/kWh, and so on:

- Raw material A: 1.00 EUR/kg
- Raw material C: 1.50 EUR/kg
- Raw material E: 2.00 EUR/kg
- Energy cost structure: Basic fee: 1,000.00 EUR
  0–3,000 kWh: 0.40 EUR/kWh
  3,001–4,000 kWh: 0.30 EUR/kWh
  4,001–5,000 kWh: 0.20 EUR/kWh
  Above 5,000 kWh: 0.10 EUR/kWh
- Waste management costs: 1.00 EUR/kg

Table 19 includes the monetary saving potentials for this case. They were calculated with the physical values from Table 18 and the corresponding price factors. For the costs and saving potentials of raw materials and energy, the different material prices and the energy pricing structure need to be taken into account. Theoretically, the saving potential of waste management costs could be quantified solely based on the physical saving potential of raw materials and the waste management cost factor as well. To point out the scenario-based approach once more, the values of the status quo scenario and the improved scenario were determined, respectively, and then the difference of the two was calculated. Both ways will lead to the same results.

Table 19: Calculation of monetary saving potential, graduated energy pricing mechanism

	Material costs	Energy costs	System costs	Waste mgmt costs	Total costs
	EUR	*EUR*	*EUR*	*EUR*	*EUR*
Status quo scenario	100+75+40 =215.0	2,563.61	70.0	50+20+10 =80	2,928.61
Improved scenario	92+69+36.8 =197.8	2,454.94	64.4	46+18.4+2 =66.4	2,783.54
Saving potential	8+6+3.2 =17.2	108.67	5.6	13.6	145.07

As in the other examples, the GHG emission factors have the same values as the cost factors in order to illustrate that the MFCA 2.0 approach equally applies to costs and GHG emissions.

- Raw material A: 1.00 kg CO_2/kg
- Raw material C: 1.50 kg CO_2/kg
- Raw material E: 2.00 kg CO_2/kg
- Energy GHG emissions: Basic emission factor: 1,000.00 kg CO_2e
  0–3,000 kWh: 0.40 kg CO_2e/kWh
  3,001–4,000 kWh: 0.30 kg CO_2e/kWh
  4,001–5,000 kWh: 0.20 kg CO_2e/kWh
  above 5,000 kWh: 0.10 kg CO_2e/kWh
- Waste management: 1.00 kg CO_2e/kg

Table 20 includes the GHG emissions-based saving potentials for this case.

Table 20: Calculation of GHG emissions-based saving potentials, graduated emission factors for energy

Scenario	Material	Energy	System efforts	Waste mgmt	Total
	kg CO_2e	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*
Status quo scenario	100+75+40 =215.0	2,563.61	70.0	50+20+10 =80	2,928.61
Improved scenario	92+69+36.8 =197.8	2,454.94	64.4	46+18.4+2 =66.4	2,783.54
Saving potential	8+6+3.2 =17.2	108.67	5.6	13.6	145.07

With the exemplary derivation of the saving potentials of the specific case that the material loss flow in QC3 can be partly reduced by 80% from 10.0 kg to 8.0 kg, the application of the scenario-based algorithm to non-linear functions has been illustrated. Skipping additional detailed calculations, the following Table 21 contains the MFCA matrix with physical values, and it includes the saving potentials of the MFCA 2.0 calculations for the cases that the losses in one of the QCs are avoided, respectively (row *Saving potential if loss is avoided in the respective QC only*), and for the case that all losses are avoided (row *Saving potential if all losses are avoided*). Additionally, the table contains the values of the remaining amounts for the different QCs if all losses are avoided (row *Amount if all losses are avoided*), which are summarized in the row *Total amounts in the product flow in this process (all QCs)*. Moreover, the row *Total amount status quo all flows* less the values of the following row *Total amounts in the product flow in this process (all QCs)* equals the values in the last row *Total saving potential if all losses are avoided*.

This table allows insights such as that the maximum saving potential in this process under analysis is 80.0 kg in materials (64.0 kg material A, 14.0 kg material C and 2.0 kg material E), 1,842.93 kWh in energy and 25 EUR in system costs. These figures are based of the theoretical assumption that all three loss flows are avoided. Moreover, the reduction of the material loss flow in QC1 has the highest material saving potential (50 kg material A), QC2 has the highest energy saving potential (1,080.0 kWh) and QC3 has the highest system cost saving potential (17 EUR). The table values are additionally represented graphically in Table 21.

Table 21: MFCA matrix, non-linear energy demand including MFCA 2.0 (grey background), physical values

MFCA matrix	QC 1			QC 2			QC 3		
	Material	Energy	System costs	Material	Energy	System costs	Material	Energy	System costs
	kg	*kWh*	*EUR*	*kg*	*kWh*	*EUR*	*kg*	*kWh*	*EUR*
Inputs from previous QC				50	500.0	12.5	80	2,400.00	30
New inputs in QC	100	1,000.0	25.0	50	2,500.0	25	20	818.04	20
Total in each QC	100	1,000.0	25.0	100	3,000.0	37.5	100	3,218.04	50
Product of QC	50	500.0	12.5	80	2,400.0	30	90	2,896.24	45
Material losses (following ISO 14051:2011)	50	500.0	12.5	20	600.0	7.5	10	321.80	5
Total losses	50	500.0	12.5	70	1,100.0	20	80	1,421.80	25
Saving potential if loss is avoided in the respective QC only	50	750.0	12.5	20+10 =30	360+720 =1,080.0	5+5 =10	10+5+2 =17	190+380+9.33 =579.33	10+5+2 =17
Saving potential if all losses are avoided	64	870.4	16.0	14	963.2	7	2	9.33	2
Amount if all losses are avoided	36	129.6	9.0	36	1,536.8	18	18	808.71	18
Total amount status quo all flows	170	4,318.04	70.0						
Total amounts in the product flow in this process (all QCs)	90	2,896.24*	45.0						
Total saving potential if all losses are avoided	80	1,842.93	25.0						

* This does not equal the minimum total energy demand (129.6 kWh + 1,536.8 kWh + 808.71 kWh = 2,475.11 kWh) if all losses are avoided because the value of the product applies a linear approach. MFCA 2.0 applies a scenario-based approach, embracing the non-linear energy demand of the different QCs in this application example.

Figure 51: MFCA 2.0 Sankey diagram, material loss in QC1 is avoided, non-linear energy demand—physical flows

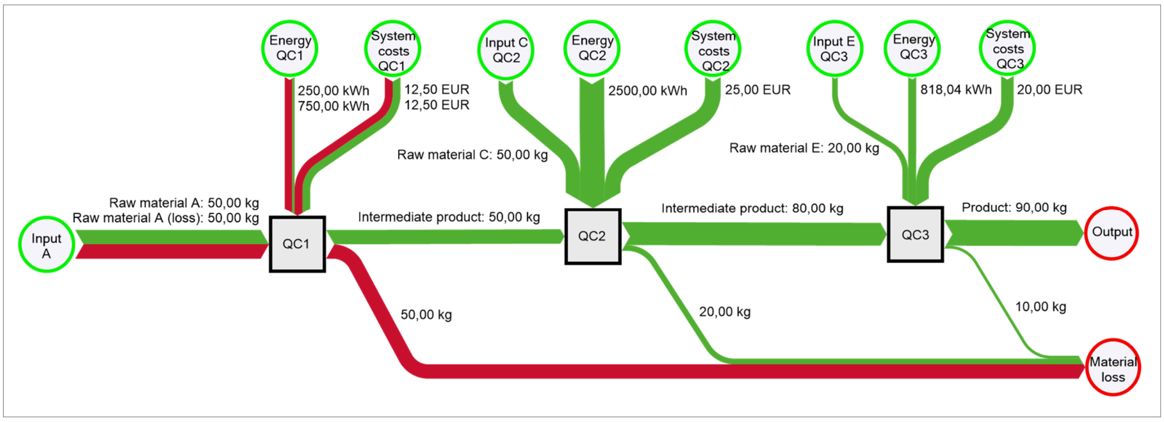


Figure 52: MFCA 2.0 Sankey diagram, material loss in QC2 is avoided, non-linear energy demand—physical flows

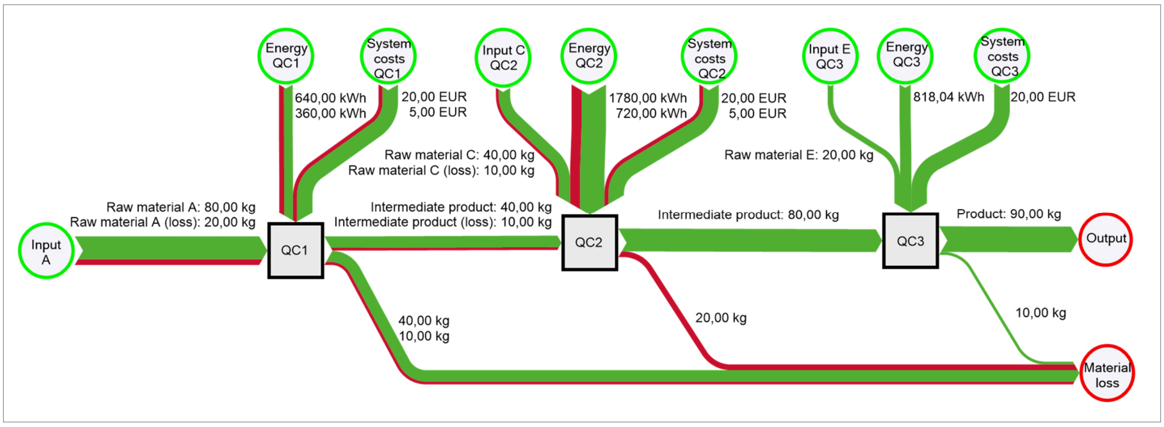


Figure 53: MFCA 2.0 Sankey diagram, material loss in QC3 is avoided, non-linear energy demand—physical flows

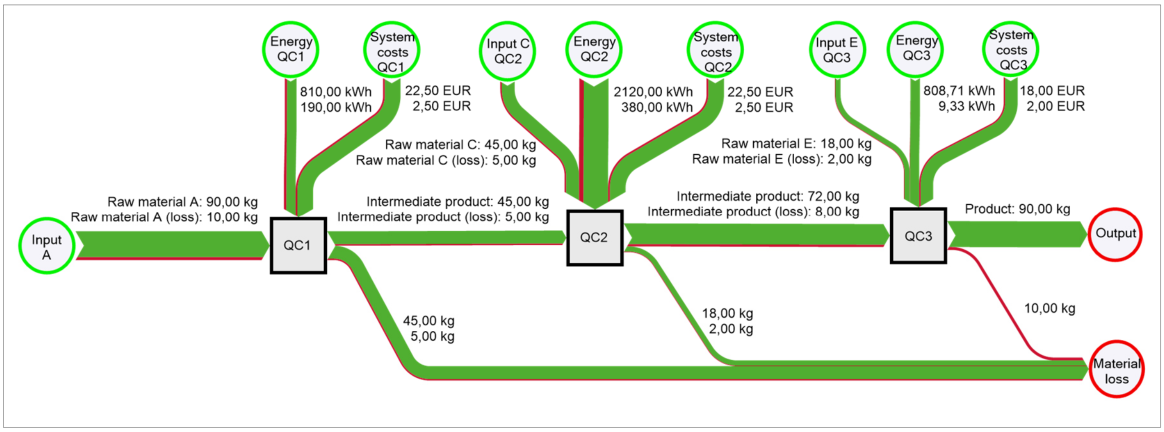
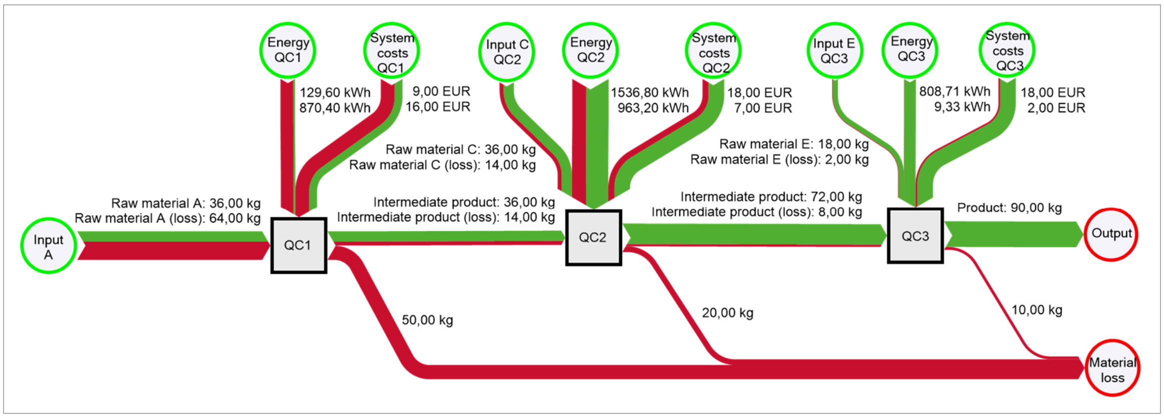


Figure 54: MFCA 2.0 Sankey diagram, all three loss flows are avoided, non-linear energy demand—physical flows



This table and the flow diagrams can be a starting point for further analyses as they give an overview of the theoretical maximum saving potentials related to the different QCs and for the whole process under analysis, as pointed out above. Furthermore, as Subsection 4.3.4 has shown, for example, with Case 4 in Paragraph 4.3.4.6 or with Case 6 in Paragraph 4.3.4.8, there is an unlimited number of other cases that can be quantified with the scenario-based approach of MFCA 2.0.

The values of the row *Material losses (following ISO 14051:2011)* are the result of the approach of MFCA 1.0. With the extended MFCA matrix, MFCA 1.0 and MFCA 2.0 can now be compared. Generally, MFCA 1.0 allocates energy and system costs to the output flows "by using an appropriate apportionment basis" (ISO, 2011, p. 11). In the example, the physical mass of the material was chosen as apportionment basis. This calculation was applied to each QC and accumulated along the process so that the total amount of the values that were allocated to the material loss flows can be found in QC3. The values are 80 kg, 1,421.80 kWh and 25 EUR. The values allocated to the product flow can be read off in the row above: 90 kg, 2,896.24 kWh and 45 EUR. In comparison, the MFCA 2.0 approach leads to different results. Since it follows the scenario-based approach, it is able to quantify saving potentials for the system under analysis as a result of a material loss reduction. The saving potential equals the differences between the status quo scenario and the improved scenario. If the relationships in the system under analysis are linear, the theoretical maximum saving potentials if all loss flows are avoided do not differ between the two MFCA approaches. However, since this example includes non-linear energy demand, the total energy saving potential differs from the amount of energy that MFCA 1.0 would allocate to the loss flows. MFCA 1.0 allocates 1,421.80 kWh to the losses, whereas the scenario-based approach of MFCA 2.0 quantifies the saving potential of 1,842.93 kWh. Consequently, the theoretical minimum energy demand under the condition that all loss flows are avoided differ as well (2,896.24 kWh for MFCA 1.0 and 2,475.11 kWh for MFCA 2.0). This numerical example exposes the logics of the two approaches. While MFCA 1.0 allocates efforts, MFCA 2.0 quantifies saving potentials as the difference of two scenarios.

Table 22 and Table 23 include the monetary and GHG emissions-based MFCA 2.0 matrixes. Energy costs and energy-related GHG emissions cannot be allocated to the different QCs since due to the graduated pricing mechanism and graduated emission factors, they relate to the whole production process, and the physical total amounts define the total energy costs and emissions, respectively. Following Riebel's (1994b) logic and identity principle, the decision to produce the product and to consume energy is the cost object in this case. Therefore, only the total amount of energy costs is shown, and the saving potentials are calculated for the whole system under analysis following the scenario-based approach of MFCA 2.0. Therefore, the QC-based fields for energy costs are intentionally left empty.

Like Table 21, the two following tables contain MFCA information in a condensed form. The numbers with the grey background are based on the MFCA 2.0 approach. The first row *Saving potential if loss is avoided in the respective QC only* contains the MFCA 2.0 results if that one material loss flow is avoided. The numbers are result of the scenario-based approach and they differ from the row *Material losses (following ISO 14051:2011)* since MFCA 2.0 takes the whole process under analysis into account. For example, if the 10 kg material loss flow in QC3 are avoided with a corresponding improvement measure, 21.5 EUR material costs, 142 EUR energy costs, 17 EUR system costs and 17.0 EUR waste management costs can be saved, leading to a total of 197.5 EUR. In comparison, the monetary saving potentials of QC1 and QC2 are 305.70 EUR and 367.20 EUR, respectively. The values for energy costs cannot be calculated for single flows or QCs because the total energy costs depend on the total energy demand. The total costs can only be calculated using the graduated prices, resulting in the total energy costs. Again, this demonstrates the strength of the scenario-based approach, while the flow-focused approach of MFCA 1.0 assumes linear relationships. Since in this fictional example price factors and GHG emission factors are identical, the figures are the same for GHG emissions measured in kg CO_2e. These tables offer a good overview of a process and its monetary and GHG emissions-based losses. They include the saving potentials of the different QCs as well as the theoretical maximum saving potential of the process under analysis. These values are a sound basis for further analyses and the search for improvement measures that reduce costs or GHG emissions.

Table 22: MFCA matrix, graduated energy pricing mechanism including MFCA 2.0 (grey background), monetary values

MFCA matrix	QC 1				QC 2				QC 3			
	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs	Material costs	Energy costs	System costs	Waste mgmt costs
	EUR	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*	*EUR*
Inputs from previous QC					50	500.0	12.5		100.0		30	
New inputs in QC	100		25.0		75	2,500.0	25.0		40.0		20	
Total in each QC	100		25.0		125	3,000.0	37.5		140.0		50	
Product of QC	50		12.5		100	2,400.0	30.0		126.0		45	
Material losses (following ISO 14051:2011)	50		12.5	50	25	600.0	7.5	20	14.0		5	10.0
Total losses	50		12.5	50	75	1,100.0	20.0	70	89.0		25	80.0
Saving potential if loss is avoided in the respective QC only	50	193.20	12.5	50	20+15 =35	292.2	5+5 =10.0	30	10+7.5+4 =21.5	142	10+5+2 =17	29.5
Saving potential if all losses are avoided	64		16.0	50	21		7.0	20	4.0		2	10.0
Amount if all losses are avoided	36		9.0		54		18.0		36.0		18	
Total amount status quo all flows	215	2,563.61	70.0	80								
Total amounts in the product flow in this process (all QCs)	126		45.0									
Total saving potential if all losses are avoided	89	573.57	25.0									

Table 23: MFCA matrix, graduated GHG emission factors for energy including MFCA 2.0 (grey background), GHG emissions

MFCA matrix	QC 1				QC 2				QC 3			
	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt	Material	Energy	System efforts	Waste mgmt
	kg CO_2e	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*	*kg CO_2e*
Inputs from previous QC					50	500.0	12.5		100.0		30	
New inputs in QC	100		25.0		75	2,500.0	25.0		40.0		20	
Total in each QC	100		25.0		125	3,000.0	37.5		140.0		50	
Product of QC	50		12.5		100	2,400.0	30.0		126.0		45	
Material losses (following ISO 14051:2011)	50		12.5	50	25	600.0	7.5	20	14.0		5	10.0
Total losses	50		12.5	50	75	1,100.0	20.0	70	89.0		25	80.0
Saving potential if loss is avoided in the respective QC only	50	193.2	12.5	50	20+15 =35	292.2	5+5 =10.0	30	10+7.5+4 =21.5	142	10+5+2 =17	17.0
Saving potential if all losses are avoided	64		16.0	50	21		7.0	20	4.0		2	10.0
Amount if all losses are avoided	36		9.0		54		18.0		36.0		18	
Total amount status quo all flows	215	2,563.61	70.0	80								
Total amounts in the product flow in this process (all QCs)	126		45.0									
Total saving potential if all losses are avoided	89	573.57	25.0									

4.3.7 Interpretation of the MFCA 2.0 Results: Interim Conclusion

After the illustration of the scenario-based approach of MFCA 2.0 with different tangible examples, this subsection focuses on the interpretation of the results and their meaning for corporate practice. This comprises the compatibility of the method with cost accounting, with the ISO standards for environmental management systems and the evaluation of improvement measures regarding their economic-ecological efficiency.

4.3.7.1 Relevance of MFCA 2.0 for Cost Accounting

With the quantification of saving potentials and the assessment of improvement measures, MFCA 2.0 represents a novel form of corporate cost accounting. While cost accounting usually focuses on products only, MFCA 1.0 focuses on the costs of the losses. However, this is not expedient for the decrease of the losses or the increase of the resource efficiency of the process under analysis. MFCA 2.0 is a special form of cost accounting that is based on the modeling of material and energy flows. Through the scenario-based approach, the method is able to calculate the saving potentials of different improvement measures, thus providing cost information on different options for action. This goes hand in hand with two textbook classics. Wöhe et al. (2020) wrote a classic for business studies and management, and they emphasize that corporate management should steer and coordinate a company in a way that it develops further over time, while securing the company's existence in the long run (Wöhe et al., 2020). Horsch (2023), building on Wöhe et al. (2020), focuses on cost accounting and argues that the steering process mentioned above includes the implementation of improvement measures and the controlling thereof. Depending on the size of the company, this management task can be executed by managers or in close collaboration with controllers (Horsch, 2023). Controllers should generate, filter and prepare the information that is required for managers to make informed decisions, thus steering and coordinating the company and its activities (Horsch, 2023).

Transferring this knowledge to MFCA 2.0, the method should be applied as management and controlling instrument in a way that helps to steer, coordinate and control corporate activities. These activities can be a decision for or against the implementation of a loss-reducing improvement measure that has been evaluated with MFCA 2.0. In order to enable these informed decisions, the MFCA 2.0 results should be prepared including figures, illustrations and the gathering of related qualitative data about the improvement measures, respectively. Such management and controlling activities lead to reductions in resource demand, costs and GHG emissions, thereby contributing to the achievement of the corporate goals and the company's continued existence. MFCA 2.0 offers a genuine extension of cost accounting. It does not only point out potential cost reductions and the environmental effects of the different options for action, but it also supports their implementation and controlling. In this way, MFCA 2.0 establishes a connection between cost accounting and a company's environmental management, which the following paragraph is going to illustrate.

4.3.7.2 Compatibility of MFCA 2.0 With Environmental Standards and the Corporate Management System

MFCA 2.0 contributes to the management of a company's environmental emissions and can thus reduce its carbon footprint. With regard to corporate carbon accounting, Schaltegger and Csutora (2012) called for tangible support for corporate decision-making and the implementation of carbon management measures that reduce corporate emissions. MFCA 2.0 and the consulting concept are able to offer this support, and the combination of environmental and monetary information makes it a unique management tool.

Being part of the ISO 14000 family of standards, MFCA also contributes to environmental management systems. It is able to support the implementation of the standard ISO 14001, which is a standard for environmental management systems containing its requirements and guidance for use (ISO, 2015). Specifically, the standard addresses the planning of measures, their effects including environmental, financial and commercial effects, and how an organization should evaluate the measures' feasibility depending on the company's specific context (ISO, 2015). Moreover, the standard suggests the setting of environmental targets such as the reduction of waste, waste management and recycling of waste (ISO, 2015). The standard decidedly calls for the formulation of improvement measures and the implementation of the ones that are indispensable for the achievement of the targets that were set before (ISO, 2015). This also comprises innovative changes such as measures that reorganize processes. Once such an improvement measure has been implemented, it should be monitored, measured and continuously evaluated to ensure its effectiveness (ISO, 2015). The standard ISO 14004 contains general guidelines on the implementation of an environmental management system (ISO, 2016). To some extent, it can be understood as recommendation for MFCA because it endorses the use of any tool preventing or reducing the generation of waste and pollution, which in turn reduces the company's environmental footprint (ISO, 2016). The standard explains that this can be achieved through a variety of changes such as the substitution of material or energy, recycling or an increase in the efficient use of material and energy resources (ISO, 2016). Moreover, it demands the definition of targets based on performance figures like waste generation per product unit and efficiency figures for material and energy inputs. The pursuit of these targets should always follow the PDCA cycle (ISO, 2016).

The systematic implementation and use of an environmental management system following the ISO standards 14001 and 14004 can be substantially enhanced by the use of MFCA due to its focus on material losses. With its goal of an actual reduction of material losses and the resulting increase in resource efficiency, MFCA 2.0 pursues both ecological and economic goals in a transparent and data-driven way. This enables management to take responsibility, contribute to the fulfilment of the SDGs and thus take corporate social responsibility more seriously, which is becoming increasingly relevant (Kokubu et al., 2023; Kokubu et al., 2022). MFCA 2.0 is therefore an appropriate method to gradually achieve the standards' goal to implement and use an environmental management system. The following chapter describes the consulting concept accompanying and complementing the MFCA 2.0 method.

5 The Consulting Concept: Bridging the Gap Between Theory and Practice

The proof of the pudding is in the eating.—British proverb
Experientia est optima rerum magistra.—Latin proverb

The reborn method of MFCA as MFCA 2.0 is complemented with a consulting concept accompanying the implementation and continuous use of the method in a corporate context. The consulting concept explains and illustrates MFCA 2.0 by clarifying prerequisites such as data collection and handling and the formulation of specific questions that MFCA 2.0 can answer. This chapter provides guidance on how to initiate, communicate and implement the method among staff and across departments in order to improve the company's resource efficiency, thereby making it more sustainable from an environmental and economic point of view.

5.1 The Purpose of Consulting Based on MFCA 2.0

Management consulting can be traced back to time of the industrial revolution when a new understanding of the term *factory* was born that initiated manifold transformation processes (Kubr, 2002). In the second half of the 19th century, the scientific management movement was born as the result of entrepreneurs who had the wish to improve their business activities with broadly applicable methods and principles (Kubr, 2002). The emerging consulting industry became known and popular for its focus on productivity and the elimination of waste, which in turn saved resources both in the narrow and in the broad sense (Kubr, 2002).

MFCA offers a new perspective on corporate production processes and cost accounting practices, which is not an end in itself. Schmalenbach—a pioneer of business administration and cost accounting—had realized that the bookkeeping department is able to provide cost information on the past at most, but not for the purpose of pricing decisions affecting the future (Pfaff, 2017). Therefore, he established the concept of cost calculations for the purpose of determining and controlling costs with regard to the future. In a similar way, the purpose of MFCA 2.0 needs to be carved out and stated. Riebel's cost accounting system is based on a purpose-neutral accounting database (cf. Subsection 2.5.2) and in the next steps, the data can be processed and adapted for a specific purpose (Riebel, 1994a). Therefore, the following two-step process was introduced to MFCA 2.0 to implement the method.

The first step of MFCA 2.0 represents the collection of data and the creation of an MFCA model. The second step includes the analysis of the model regarding a specific question or problem. This approach allows the efficient implementation of the new MFCA 2.0 approach: It supports the purpose-neutral data collection on the one hand and the purpose-specific application thereof in order to support management decisions on the other hand. Prior to the implementation of the second step, the framework conditions of the following calculations need to be defined and communicated. These conditions include the process conditions of the system under analysis and the specific, goal-oriented formulation of a question that can then be discussed and answered with the MFCA 2.0 results. MFCA 2.0 uses process data to pursue a specific purpose and thus guarantees additional value for the company. MFCA is not a tool solely increasing transparency, but it was developed as a tool that offers tangible purpose-driven support in the form of planning and controlling losses to increase resource efficiency.

The following ideas shall provide a basis for the understanding of the consulting concept related to MFCA 2.0. Since consulting is not an appearance of the present time, the article informatively titled “Consulting Is More Than Giving Advice”—written and published in the *Harvard Business Review* in 1982 by Arthur N. Turner was consulted. Turner's (1982) main point is that any management consulting project should start with a clear statement about the project’s purpose in order to be able to manage expectations and increase satisfaction throughout the collaboration. Therefore, the client’s needs are to be understood and translated into one or multiple purpose(s). Throughout his article, Turner (1982) introduces a hierarchy of eight consulting purposes, which increase in meaning and difficulty:

1. Providing information to a client
2. Solving a client’s problem
3. Making a diagnosis, which may necessitate redefinition of the problem
4. Making recommendations based on the diagnosis
5. Assisting with implementation of recommended solutions
6. Building a consensus and commitment around corrective action
7. Facilitating client learning
8. Permanently improving organizational effectiveness

With regard to MFCA 2.0, this hierarchy of purposes offers food for thought and sharpens the method’s practical orientation. Although the provision of information (1.) may seem self-evident, it should not circumvent the question of how, when, where and by whom the information will be processed. These are no controlling questions, but instead, they may bring underlying expectations and goals to light, thus supporting the effective application of the method. Due to its unusual perspective, MFCA enables transparency regarding losses. The further investigation of the losses is likely to be decisive in the search for a solution to a specific problem (2.). Since MFCA offers a new perspective on existing processes, this can entail a change of purpose for the project, which should be seen as positive development. Consequently, the next higher purpose is a diagnosis of the problem, which represents the understanding of how and why losses exist including their point and time of origin. Understanding and defining the problem in this way is a crucial step in MFCA 2.0, as will be explained further in Section 5.4. Once the problem has been understood and defined, recommendations can be formulated and communicated. After certain measures have been identified and evaluated, MFCA 2.0 will be able to frame recommendations as a result of a dialog with the company representatives involved in the analysis.

Until this point in the hierarchy, Turner (1982) describes the purposes of consulting as rather traditional. He describes the following three purposes as additional goals. They do not need to be stated at the beginning of the collaboration between the consultant and the client company, but they will be fulfilled once the traditional purposes of consulting have been achieved successfully (Turner, 1982). These additional goals comprise the assistance with the implementation of measures from the consultant, the development of a support concept for the corporate staff, and the initiation of a learning process (Turner, 1982). The last goal will foster the ability of the company to handle and overcome comparable challenges in the future (Turner, 1982). These goals are transferable to MFCA 2.0 very well because the method aims to increase resource efficiency through the implementation of tangible measures, which the consultant can accompany and support. Moreover, a successful MFCA 2.0 project invites the corporate staff and also convinces them of the improvement measures in case they have not been involved in the search for measures, the evaluation thereof or in decision-making. Since MFCA 2.0 was not designed as one-time application, the engagement of an external consultant should be understood as a starting signal of the learning process. The consultant should work out and increase the company's awareness of losses and demonstrate and teach ways how to reduce losses. Once the MFCA 2.0 approach has been understood by the staff and integrated in the company's way of thinking, it can successively reduce losses and thus increase resource efficiency of the processes under analysis. This is an aspirational learning result that builds in-house expertise for resource efficiency. In an ideal situation, the consultant does not only initiate a learning process in the areas in which they engage with the company, but their work also impacts the company as a whole. The goal is not to generate recommendations. Recommendations are rather a means to an end, which is the improvement of the company's performance through more effective processes (Turner, 1982).

What Turner described as organizational effectiveness that keeps the company viable in 1982 could be interpreted as resilience and sustainability in today's business context, which are both highly relevant to ensure future competitiveness. The reduction of losses and the consequent increase in resource efficiency are specific and practicable steps in this future-oriented direction. A more recent approach to consulting uses the concept of the blind spot to explain the purpose of consulting for companies (Väth, 2019). Reasons for blind spots can be habituation effects that, for example, lead to careless mistakes, but also aspects related to how the company is structured and organizes itself (Väth, 2019). Väth (2019) points out that blind spots do not necessarily grow over time because they can also be the result of flaws that are difficult to spot from within the company. Therefore, he argues, an external perspective like that of a consultant can point out such blind spots and support the company in reducing or even eliminating them.

The purpose of MFCA 2.0-based consulting will be summarized with the following four aspects. At the beginning of the consulting project, MFCA 2.0 formulates a goal-oriented, specific question. Based on this question, the consulting process will be carried out in close cooperation with the appointed employees of the company. In order to initiate a learning process and to empower the employees, their experience and viewpoints will be matched with the external view of the consultant. The MFCA 2.0 consulting process will strive to make the process under analysis more resource efficient and increase its organizational effectiveness. This will increase the company's sustainability and its future competitiveness beyond the scope and timeframe of the consulting project.

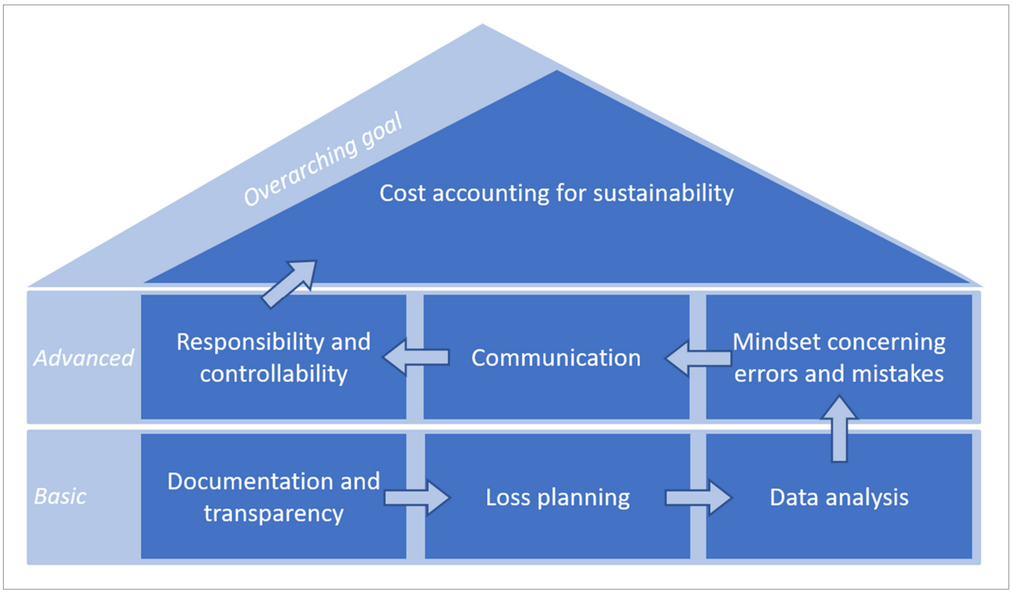
5.2 MFCA in Corporate Practice: An MFCA 2.0 Consulting Concept

MFCA 2.0—being inspired by the cost accounting debate between Kilger and Riebel—is accompanied by a consulting concept in order to encourage its application in corporate practice. The MFCA 2.0 consulting concept comprises the seven guiding principles which together provide the framework for a successful implementation for MFCA 2.0. When designing the consulting concept, many ideas from the history of cost accounting—especially from Riebel's and Kilger's works—were taken up. An important strength of *Kilger's Flexible Standard Costing and Contribution Margin Accounting* is that he closely cooperated with Plaut who had recognized the demand for a new costing approach in practice (Kilger, 1993). In their cooperation, marketing activities such as the dissemination and teaching of their new approach to their target audience, for example, at conferences or in the form of seminars were important factors for the acceptance of their approach in corporate practice (Kilger, 1993, cf. Subsection 2.2.1). Moreover, Plaut founded the consulting company Plaut AG, which implemented the new approach in corporate practice. *Riebel's Generic Direct Costing and Contribution Margin Accounting* has the strength of being very accurate, although its implementation in practice is not easy, even more so at the time it was developed. Nevertheless, it offers valuable impulses for the consulting concept.

Figure 55 gives an overview of how MFCA 2.0 can be implemented in a corporate context. It is based on seven elements supporting the implementation of the method, which can be classified in the three categories *basic*, *advanced* and *overarching goal*. The order of the elements is not hierarchical, and the subsequent element does not necessarily presuppose the preceding one. Nevertheless, the elements are interrelated to a certain extent, and, for example, the execution of one element can enhance the implementation of another one. The following paragraph provides a brief overview, and each element will be explained in more detail in the following subsections.

The category *basic* enables a fundamental application of the method. It can be implemented within a single project and a given time frame that may be carried out by an external consultant. It comprises the three elements *documentation and transparency*, *loss planning* and *data analysis*. The category *advanced* enables a more embedded application of the method and thus requires more involvement on the part of the corporate management and staff, and it also requires openness to change. The three elements of this category are *mindset concerning errors and mistakes*, *communication*, and *responsibility and controllability*. Finally, the roof element in Figure 55 represents the overarching goal of an MFCA 2.0 implementation. It is named *cost accounting for sustainability,* and it can be achieved through the intentional integration and institutionalization of the method. Its focus lies on losses and inefficiencies in the corporate mindset.

Figure 55: Schematic diagram of the implementation of the MFCA 2.0 consulting concept (Own illustration)



5.2.1 *Documentation and Transparency: A Strong Combination*

The clear documentation of the data and the results is an indispensable element of the application of the method MFCA 2.0 in a corporate context—no matter if it is a one-time project or if the aim is its implementation for continuous use. The implementation of MFCA 2.0 highly depends on the data that is used. While the topic of data collection and quality will be addressed separately in Section 5.6, this element of the MFCA 2.0 consulting concept focuses on the documentation function and the increase in transparency related to the method.

Material losses are a focal point of MFCA and therefore, corporate documentation forms such as data collection sheets need to be adapted to successfully implement the method. These forms should include corresponding fields for the designation of the loss, information on its mass or volume and a specification of the cause why it occurs. Moreover, it is important to document the time horizon of the different inputs of the process under analysis. This requires a list of information on how long or until what date the cost of the inputs is going to be fixed due to contractual agreements or stockpiling that has already taken place. Once this information has been documented, it can be used to create a tabular list, e.g., sorted by mass, details about their cause or cost conditions. The data analysis will be easier after bringing the data in this format. For example, the total amount of losses with the same cause can then be calculated. A possible insight might be that the same cause is responsible for multiple losses, thus possibly making the search for an appropriate improvement measure more effective since it will reduce multiple losses at once.

Furthermore, when documenting the status quo of the manufacturing process under analysis, a value for unavoidable losses can be defined for the different losses, respectively. This value may range from zero to the value of the status quo. It is subject to the estimation of the persons who are familiar with the process and who work with it on a regular basis. This value should also be based on a reasonable and realistic attentiveness of the persons in charge of the production step, such as machine operators. It may be worthwhile considering whether these tasks can be technically supported, for example, with production monitoring software or cameras. In many cases, this value will not be zero since it is not advisable to define theoretical values that are not achievable in daily production practice. This line of argumentation finds support in the literature since employees do not always have the same understanding of the concept of loss as MFCA (Kokubu & Kitada, 2015). Managers do not only accept losses that occur along the production processes—since the process as a whole is still profitable—but they consider their processes as "almost perfect" (Kokubu & Kitada, 2015, p. 1281). Challenging this view, Kokubu and Kitada (2015) offer the alternative to consider the difference between material inputs and outputs as loss that cannot be avoided. This alternative view raises awareness of losses and hence paves the way for the MFCA approach (Kokubu & Kitada, 2015). MFCA 2.0 intends to differentiate the losses that have been documented between avoidable and unavoidable, thereby bringing the method closer to reality. For example, some losses may be technically necessary to a certain extent because they guarantee flawless products and consequently avoid rejects.

In summary, documentation of the status quo is pivotal for the implementation of an MFCA project. Moreover, it is advisable to reduce the amount of loss to the degree that is technically feasible and realistic instead of pushing unattainable goals. Based on the differentiation between avoidable and unavoidable losses, the responsibility of the cost center manager should be adapted in a way that they are only held responsible for losses which they can avoid with better production management. The example of an unforeseen drop in material quality and the subsequent production of rejects can be categorized as unavoidable at this point in time if this phenomenon had not occurred before. In this case, the cost center manager should not be charged with the loss. However, if this phenomenon had occurred multiple times already, the cost center manager should consider approaching corporate management with improvement suggestions such as improved incoming goods inspections. If the suggestions are not implemented and if there is generally no wish on the part of management to improve the situation, the answer is that this kind of loss should be categorized as unavoidable. Thereby, production management, cost accounting and MFCA 2.0 move closer together.

5.2.2 Loss Planning

Once the losses have been documented and the unavoidable amounts of losses have been determined, their impact on the input amounts can be quantified, respectively. This also works the other way around, i.e., if the input amount and the product quantity are known, their difference equals the amount of loss. If, for example, a product consists of 90 kg of material A and the amount of loss per product is 10 kg of material A, the efficiency factor of that process can be calculated as follows.

$$ef = \text{efficiency factor of a production process}$$

$$ef = \frac{product(s)}{product(s) + loss(es)} \cdot 100\% \tag{5.1}$$

$$ef = \frac{90\ kg}{90\ \text{kg}+10\ \text{kg}} \cdot 100\% = 90\%$$

As can be seen, the amount of material required to produce the desired product is larger due to the loss. The reciprocal of the efficiency is the factor that needs to be included in the MFCA 2.0 model. This factor can be used to define the required amount of material input. In the example, this input factor is determined as follows:

$$input\ factor = \frac{\text{product(s)} + loss(es)}{\text{product(s)}} \tag{5.2}$$

$$input\ factor = \frac{90\ kg+10\ kg}{90\ kg} = 1.11$$

Once these values have been determined, they can be used to build the MFCA 2.0 model. Kilger (1993) also addressed this topic in his research on cost accounting, and he named the two indicators *yield coefficient* [own translation][33] (p. 145) and *input factor* [own translation][34] (p. 145). They are important when calculating and planning production costs.

With MFCA 2.0, the use of these indicators can be reevaluated. They are important process indicators when planning and modeling a production process with MFCA 2.0. Although this may seem logical and obvious, the consequences should not be underestimated. These mathematical equations and calculations need to be explained to management with regard to corporate resource efficiency and sustainability activities. They provide a solid basis for a discussion of the processes under analysis. Moreover, they pave the way for measures that increase the efficiency factor and hence lead to a decrease of the input factor.

5.2.3 Data Analysis

Once the required data is available in an appropriate and processed form, the next step includes the analysis of the data based on MFCA 2.0. The scenario-based approach of MFCA 2.0 has been explained using specific examples and different cases in Section 4.3. This approach offers

[33] Own translation, original in German: "Ausbringungsmenge" (Kilger, 1993, p. 145)
[34] Own translation, original in German: "Einsatzfaktor" (Kilger, 1993, p. 145)

a manifold number of ways to analyze the data. It is up to the company to decide what specific questions the analysis shall answer. That, in turn, depends on the options for improvement measures since the data analysis should only cover scenarios that are realistic in two respects: First, there needs to be a specific improvement measure whose implementation will lead to the improved scenario. Second, the reduction of one or multiple material losses in the system under analysis needs to be quantified with a value that can realistically be achieved through the improvement measure. The saving potentials can then be determined with the scenario-based approach. Based on the material and energy flow model, the associated monetary and GHG emissions-based saving potentials can be determined as well. Section 5.4 offers more information on what the search for adequate, eco-efficient and eco-effective improvement measures looks like. The analysis can also deal with scenarios that include more than one improvement measure at a time, which can lead to overlay effects that the algorithm behind MFCA 2.0 is able to quantify. This is a central element of MFCA 2.0 and it was already described by Kilger (1993). In a section on rationalization as a result of analytical cost planning, Kilger (1993) describes an example of how the implementation of an improvement measure can lead to secondary effects. In this example, the measure of a changed storage location and hence improved storage conditions led to the decrease of the company's oil demand (Kilger, 1993).

The results of the different scenarios can be summarized in the form of a tabular overview as shown in Table 12 (p. 124 in Paragraph 4.3.4.10) or in a graphical representation as it is shown in Figure 42 (p. 124 in Paragraph 4.3.4.10) for the example, respectively. This kind of data analysis is a flexible and effective way to apply MFCA 2.0. Once it has been established and coordinated well within the company, is can be conducted regularly. For example, a team of designated people can meet once a month to review the current material loss data including the costs and GHG emissions resulting from these losses. After these meetings, inspections can be made and conversations can be held on the shop floor to improve the understanding of the data. Based on the insights, the team members can develop and discuss different ideas for improvement measures once per quarter. In these meetings, the period for the analyses needs to be defined as well. Depending on the time horizon, some flows may be fixed or flexible and consequently, some flows may be considered fixed for a certain scenario. This makes the MFCA 2.0 method and its results more realistic since the saving potentials depend on the changeability of the different flows. For example, the replacement of an old production unit through a newer, smaller one may reduce a company's space requirements, but it also takes time since rental contracts usually comprise notice periods. In case the company would like to use the space differently once it becomes available after the implementation of the improvement measure, the decision about its new utilization and its assignment to a different cost center also takes some time.

In conclusion, the data analysis contains aspects that are company-specific and consequently, the analysis should be handled company-specific. This customized approach of MFCA 2.0 makes the method more flexible regarding its context-specific application and hence increases the significance of the results in a way that the saving potentials and their time reference are more realistic.

5.2.4 The Corporate Mindset Concerning Losses due to Mistakes

The fourth element of the consulting concept addresses a company's mindset concerning errors and mistakes. Just like some losses cannot be avoided completely and hence the corresponding loss flow cannot be reduced to zero, mistakes cannot be eliminated completely. There are two reasons for this. First, models and calculations of production processes usually assume ideal production conditions and are therefore theoretical to some extent. They cannot always be realized exactly the way they have been sketched out with pen and paper. One reason is that there are forces and natural laws at work that cannot always be thought through in the planning or modeling stage. The second reason lies in the natural law that human beings make mistakes from time to time. This is certainly not a justification for mistakes, but it should sensitize the people involved that unplanned losses cannot be reduced to zero because they are unavoidable to a certain extent.

Furthermore, mistakes should not be seen as purely negative because they offer an opportunity for improvement in the form of an increase in resource efficiency. A mistake is an opportunity to analyze its causes and context in detail and to sensitize the people involved. In this way, the production conditions can be improved or stabilized. Mistakes make production processes more transparent, and they can initiate and support learning processes in a company.

5.2.5 Communication

The application of MFCA 2.0 relies on communication between the different participants and departments within the company. Additionally, MFCA 2.0 encourages communication across departments since the method requires a variety of physical, financial and environmental data. Generally, communication form and content should be adapted to the company's individual communication style to make it easier for the readers and listeners to identify themselves with the content and hence with MFCA 2.0.

Communication processes can be supported with structured meetings in which, for example, department representatives can present, review and discuss the status of the method's implementation. Such round tables are an important pillar of any MFCA 2.0 project since they offer room for possible inquiries and the framework of the project's further course. Therefore, the participants should be able to make decisions in these meetings regarding the next steps, thus promoting the implementation of the method in an unbureaucratic way.

The documented data including the causes of the material losses, the data analysis, the description of the different improvement measures, the derived scenarios and the quantified saving potentials can be compiled in the form of an MFCA 2.0 report. As the report grows chapter by chapter, it can be made available to a selected group of people such as certain managers and employees. By allowing comments and questions in the document, this can be an opportunity to give feedback, thereby improving the implementation and effectiveness of the method. Once the results are final, they can also be communicated in an edited and shortened version with relevant stakeholders such as customers in order to show that the company actively engages with the topics of resource efficiency and sustainability.

This form of clear and open communication will contribute to the quality and success of the MFCA 2.0 implementation, whether it is intended as a one-time project or for the continuous use of the method. It can also have positive internal effects on a company's awareness of resource efficiency entailing cost and GHG emission reductions. This can be an important learning success because a commonly held belief among managers is—or perhaps was, with regard to the fact that the following source was published 17 years ago—that sustainability management causes additional costs and has adverse effects on a company's financial profitability (Schaltegger et al., 2008).

The standard ISO 14051 (ISO, 2011) contains a case study in which MFCA 1.0 was conducted in a large pharmaceutical company. The case study is remarkable because the MFCA results led management to introduce continuous and improved real-time data collection in an ERP (enterprise resource planning) system. More than 150 employees belonging to a wide range of functions and departments like operations, logistics or environmental management were given access to this data so that they are empowered to immediately analyze the data relevant for their function with the software application (ISO, 2011). Furthermore, corporate top management requested regular reports about material postings in the system including information on material losses and their causes (ISO, 2011). This case study demonstrates that communication, management decisions and practical actions like the purposeful investment in an ERP system determine each other, and it suggests that these elements are indispensable for the successful application of MFCA 2.0 as well.

5.2.6 Controllability and Responsibility

The sixth element comprises the two principles controllability and responsibility. This element highly depends on the preceding five elements of the MFCA 2.0 consulting concept. The *controllability principle* is a principle that was developed by Choudhury in 1986. He based his work on Solomons who had recognized and described the underlying mechanisms and forces already in 1965. The idea is that whenever the performance of divisional management is evaluated, it should be made sure that the factors influencing the performance of that division is also in the area of their influence (Solomons, 1965). If that is not the case, Solomons (1965) argues, the particular performance should not be included in the evaluation. Choudhury (1986) developed these ideas further and formed the term *responsibility accounting*. Responsibility accounting is an accounting approach which first of all demands a definition of the areas of which a manager is in control, which may turn out to be a time-consuming task (Choudhury, 1986). Second, responsibility accounting—as its name suggests—strives for the just distribution of responsibilities between managers (Choudhury, 1986). However, if the definition in the first step lacks accuracy and an appropriate level of detail, the aim of the second step—the just distribution of responsibilities—will not be achieved either. As a result, responsibility accounting and controllability are closely related to each other.

When Kokubu and Kitada (2015) relate MFCA to existing management perspectives, they apply the principle to material losses occurring in a company. They argue that a manager should only be held accountable for the losses which they are able to control. When designing an organization’s management system and introducing performance indicators, it should be made sure that the area of control fully corresponds with the area of responsibility (Kokubu & Kitada, 2015). If this condition is fulfilled and MFCA is aligned with the existing management system, the method can be applied successfully in the long run (Kokubu & Kitada, 2015). The authors point out that these viewpoints and changes in combination with the introduction of MFCA may cause conflicts for two reasons. First, the method makes losses a subject of discussion and it goes even further by interpreting losses as cost carriers. This is likely to stand in contrast to the goals of production management. Second, the additional responsibility regarding the newly identified losses can be met with rejection by managers because they may find that they cannot influence their occurrence (Kokubu & Kitada, 2015). This leads to feelings of injustice and frustration, which in turn reduce motivation and job performance. The analysis of the supply chain can lead to a solution since the cooperation with suppliers is oftentimes a promising approach (Kokubu & Kitada, 2015).

These ideas were taken up, adapted and included in MFCA 2.0. As Sections 4.2 and 4.3 explained, MFCA 2.0 allocates all costs to the product. The loss(es) are thereby released from their function as cost carrier(s). This brings the method in line with conventional cost accounting and additionally, MFCA 2.0 accomplishes a shift of focus away from losses to realistic saving potentials. This shift reframes the approach of the method in a way that it pursues the realization of saving potentials based on loss reductions, thus achieving an increase in resource efficiency. This improvement-oriented approach has a more positive connotation than the mere designation of losses.

When assigning responsibilities for the different processes including the losses and realistic saving potentials in the context of MFCA 2.0, the controllability principle should be considered. In other words, responsibility should only be assigned if the losses can be controlled and avoided by the carriers of the responsibility. If there are unavoidable losses and hence theoretical saving potentials that cannot be realized, these losses should be excluded from the aforementioned scope of responsibility. Moreover, this kind of responsibility should be framed in a positive light. Instead of holding individual employees such as managers responsible for the avoidable costs and the reduction of material losses, positive wordings such as “the search for and use of saving potentials” can be used. Moreover, this responsibility can be shared among multiple people. This can be an existing team or a group of managers that form a new team for the purpose of MFCA 2.0. The team can also be given a meaningful name such as “resource efficiency team steel” or “team saving potentials cutting processes”. Since a team is greater than the sum of its parts, it promises better results. Nowadays, more and more companies strive to build a team-oriented culture and flat hierarchies, which is why the wish to assign the responsibility to a single person should be critically reviewed.

When measuring the effectiveness of these team responsibilities and activities in the form of improvement measures, holistic thinking and correct measurement are crucial. The aim is not meticulous jurisdiction, but real improvement. Therefore, when measuring the effect of one or multiple improvement measure(s), this figure should consider the company-wide effect which may differ from the local situation. The effects of improvement measures can be quantified with the scenario-based algorithm of MFCA 2.0. When defining the improved scenario, all effects resulting from the loss reduction in the system under analysis are captured. The difference between the two scenarios represents the saving potential of the improvement measure. This avoids punctual improvements that can lead to additional losses elsewhere along the production route, thereby increasing the method’s meaningfulness and acceptance within the company. Additionally, the company-wide evaluation of improvement ideas enhances the awareness of losses and increases the motivation to look for improvement measures—even if they occur or lead to effects outside of the team’s range of responsibilities. Moreover, an improvement measure may require the cooperation between teams. Once the improvement measure has been implemented, all teams involved in the cooperation should be given credit to ensure a fair appreciation of improvement activities. Possible motivations for an increase in resource efficiency within a company can be an annual award ceremony organized by the company, an increase in the team event budget or an activity of the team’s choice such as a special training session.

To summarize, the principles controllability and responsibility are important stepping stones for the effective implementation and continuous use of the MFCA 2.0 method in a corporate context.

5.2.7 Cost Accounting for Sustainability

The final element *cost accounting for sustainability* represents the overarching goal of the consulting concept. This element uses a cost accounting approach and connects it with the concepts of resource efficiency and the reduction of GHG emissions. MFCA 2.0 opens new spheres of influence to the cost accounting discipline as a reduction of material and energy requirements contributes to a reduction of GHG emissions and resource conservation. The combination of physical values with the quantification of costs and GHG emissions offers many application possibilities such as the calculation of GHG abatement costs as a decision criterion (cf. Paragraph 4.3.4.10). Since all expenditures are allocated to the product, it can be integrated as complementary add-on to existing cost accounting practice, as Günther, Rieckhof, et al. (2017) have suggested in their analysis as well.

Considering the purpose of cost accounting—to provide rational information for operational management and decision-making (cf. Section 2.1, Horsch, 2023)—MFCA 2.0 with its sustainability perspective offers a versatile—although unusual—cost accounting management tool. It is a management tool that can be adapted to the company-specific context. For example, from the three dimensions physical, environmental and monetary, one dimension can be selected and the level of detail of the analysis can be specified. The data collection and documentation thereof can be started at a relatively low level. Once a certain level of experience with the method has been gained, the documentation level can be increased, and additional dimensions can be added. A second example is a company's wish or decision to focus on its carbon footprint, i.e., its GHG emissions. Generally, the effectiveness of the method and possible improvement measures grows as the method's scope of implementation gets increased. For example, if all corporate production processes are included, MFCA 2.0 can increase the transparency of the production-related GHG emissions and hence, more effective improvement measures that reduce the corporate carbon footprint can be derived.

In this way, MFCA 2.0 can function as a management tool striving for practical, user-driven improvements. Due to the flexibility that was described, MFCA 2.0 can be applied in parts, and the related consulting concept can also be implemented stepwise. Instead of building a company-internal team right away, the method can, for example, offer a first estimate and derive improvement measures with the help of external consulting as pointed out in Section 5.1. Depending on the company's capacities, these results can be developed further, and corporate know-how can be built, for example, with the help of trainings, work groups and projects. In this way, MFCA 2.0 can gradually contribute to the sustainable development of the company.

5.2.8 Dissemination and Promotion of MFCA 2.0 and the Consulting Concept

Just like seeds need well-prepared soil to sprout, MFCA 2.0 and the consulting concept should not be expected to automatically disseminate. Referring to the development of flexible standard costing, the role of the association AGPLAN needs to be understood and recognized (cf. Paragraph 2.2.1.4). The association organized conferences, seminars and papers, and it thereby enabled corporate learning of new cost accounting approaches. Learning from this course of development, the dissemination of MFCA 2.0 should also be supported in different ways since it is a powerful method to increase resource efficiency and thus contribute to sustainable development of the manufacturing industry.

First, it is important to present MFCA 2.0 not as a purely technical method because it contains several organizational and management-related aspects that are critical for its effective functioning. The new algorithm described in Section 4.3 is quantitative and the improvement measures oftentimes technical. However, this does not reduce the importance of the different elements of the consulting concept, which are required for a successful and sustained application of the method. Therefore, the method should be described and recognized as a combination of quantitative, technical and qualitative elements. Consequently, consulting services should acknowledge the method's non-technical aspects and describe it at least in parts as process consulting. This line of argumentation finds support in the literature. A research project on material efficiency and resource conservation addressed the topic of resource efficiency regarding potentials and appropriate political measures (Kristof et al., 2010). Moreover, an implementation concept was developed in the project. The authors also analyzed that consulting is oftentimes too focused on technical solutions. Therefore, they suggest making consulting for resource efficiency more process-oriented (Liedtke et al., 2010). Section 5.3 will explain this differentiation in more detail.

Second, public promotion and subsidies such as state agencies and consulting services free of charge should be considered. This can be an important aspect if the method is unknown or personnel capacities are small. The process-related approach of the MFCA 2.0 consulting concept will involve the corporate project members in a way that they learn and profit from the project, even if their availability is limited. Therefore, public promotion combined with financial incentives are decisive for the method's dissemination. Additionally, lighthouse projects should be published and communicated effectively to explain and illustrate the method with tangible examples. This will raise interest in the method and foster its dissemination. Promising ways of publication and communication are conference talks, social media business platforms such as Xing and Linkedin and events of industry associations such as round-table discussions and newsletters. A large number of case studies has been published in Germany with *100 Pioneers in Efficient Resource Management* (M. Schmidt et al., 2019) and further case studies on resource efficiency and process optimization (e.g., iPoint-systems GmbH, 2023). However, such publications should be continuously created and made available to the public in different forms since the subject is of topical interest to research and industry. In light of the growing sustainability challenge and the necessary reduction of GHG emissions, it is essential for the manufacturing industry to increase the resource efficiency of its processes in order to be competitive in the future. MFCA 2.0 and the consulting concept represent a useful extension to cost accounting because they support the increase a company's resource efficiency, and they should be disseminated and promoted as such.

5.3 The Consultant Team: A Purposeful Cooperation

An MFCA 2.0 consulting project requires different competencies which do not necessarily need to be united in one person. Three competencies that are required for a successful consulting project based on MFCA 2.0 are methodical expertise, technical understanding and the competence to implement the selected improvement measures.

Consulting should be understood as a two-way venture, in which both the consultant and the company have a learning experience—an aspect that Turner (1982) expresses in his article. First, he emphasizes the *facilitation of client learning* as a purpose and an additional goal of consulting. Moreover, Turner (1982) explains that the consultant should learn from resistant (re)actions or behavior on the part of the client and, building on that, address these needs and hence improve the collaboration. In the 13th edition of Kilger's work, Kilger et al. (2012) describe the idea of the *cost engineer* who should have physical, chemical and technological knowledge in order to not only precisely estimate and calculate the costs, but to also be able to develop ideas for measures how to increase the production efficiency. Therefore, the combination of economic basic knowledge and knowledge in the field of engineering is desirable when planning and analyzing costs in production systems (Kilger, 1993).

The literature on the subject of consulting differentiates between expert consulting and process consulting (Ellebracht et al., 2018; Ennsfellner et al., 2014). Expert consulting is specialized on a certain topic, e.g., a technical field of expertise. The role of the consultant is to focus on this defined problem and to develop a solution with the help of his technical expertise (Ennsfellner et al., 2014). Expert consulting is characterized by a consultant who works independently in comparison to process consulting. To carry out a successful expert consulting project, little interaction with the company that engaged them is required. The consultant relies on their technical understanding and experience when developing a solution to the defined problem that was handed over to them (Ellebracht et al., 2018). Examples that require expert consulting are the moderation of an event, process analyses or the review of a marketing strategy (Ellebracht et al., 2018).

Process consulting, on the other hand, has a different purpose and character than expert consulting. It accompanies corporate processes that search for a solution or focus on decision-making (Ennsfellner et al., 2014). Interestingly, much of the technical competence is already present within the company, and it is the task of the process consultant to carve out this knowledge together with the employees (Ennsfellner et al., 2014). To do that, the consultant gathers information, makes observations and hence opens new perspectives (Ellebracht et al., 2018). The goal of process consulting is not to present a final solution, but to help the client to develop a good solution, requiring close coordination, communication and collaboration between the consultant and the client (Ellebracht et al., 2018). The strong involvement of the client company creates feelings of responsibility and ownership, thereby increasing the dedication and positive impact of the project. This line of argumentation corresponds with Turner (1982) who stated that it is helpful to include employees in the diagnosis of the consulting subject. The participation of employees enables a change of perspective and invites them to take an active part in the search for a good solution. Moreover, the involvement of the employees leads to a greater identification with the method and makes the implementation of solutions in practice easier (Ellebracht et al., 2018). An MFCA project should not be carried out over the employees, but in cooperation with them.

Schein's (1998) classic *Process Consultation Revisited: Building the Helping Relationship* emphasizes the relationship between consultant and the client company as the starting point and as the goal of process consulting. Unlike expert consulting, building on technical approaches and methods, process consulting aims at building a helping relationship (Schein, 1998). Schein argues that any entrepreneurial activity and therefore any company has a human dimension that can ultimately only help itself or receive help for self-help. If this axiom of process consulting is not acknowledged, expectations placed on the consultant may be not fulfilled in the consulting project (Schein, 1998). Moreover, process consulting should initiate a learning process and aim at a learning success, which is in line with Turner's (1982) message that the facilitation of client learning represents an additional goal of consulting (Väth, 2019). Pure expert consulting, on the contrary, bypasses this learning process.

When applying MFCA 2.0, a certain amount of expert knowledge about the method and technical expertise with regard to the specific application are fundamental. Nevertheless, a consulting project working with MFCA 2.0 should pursue a process consulting strategy because the goal is not to hand over a defined problem to an external consultant who then develops a solution. Instead, the goal is to get a good understanding of the material losses, their context and their influencing factors. Together with the corporate staff, they can activate the company-internal knowledge to develop solution ideas in the form of improvement measures, which ultimately reduce the material losses identified and quantified with the MFCA method.

The aforementioned research project with a focus on material efficiency and resource conservation developed the idea of consultant tandems who combine technical expertise with implementation competence (Liedtke et al., 2010). They describe that in corporate consulting, technical aspects are oftentimes prevailing. Moreover, the researchers suggest a structured and intentional training of consultants who can then make a positive impact on the industry, e.g., via industry associations and business networks (Liedtke et al., 2010). This suggestion can be transferred to the consultant team applying MFCA 2.0 since the three competencies methodical expertise, technical understanding and implementation competence are required for a successful

MFCA 2.0 project. Therefore, the MFCA 2.0 consulting concept proposes a consultant triad. Depending on each consultant's background, the consultant team can consist of up to three consultants.

The methodical expertise relates to the MFCA method in general and to the methodological advancement that has been developed with MFCA 2.0. While MFCA generally enables transparency and awareness regarding losses, MFCA 2.0 allows a holistic assessment and the comparison of different improvement options. Technical understanding is required to derive improvement measures that lead to a reduction of the losses identified and quantified with the help of MFCA. Kilger et al. (2012) describe this competence as the ability to "recognize rationalization opportunities"[35] (Kilger et al., 2012, p. 252). The following Section 5.4 will address the question of how to find such measures. Once one or several measures have been chosen, they need to be implemented in the production system. This requires implementation competence, and it should not be underestimated since a lack in this area may endanger the success of the consulting project. Following the PDCA cycle (cf. Section 3.6), the implementation of one or multiple improvement measures according to the act step is what leads to the actual reduction of losses. Therefore, a consulting project based on MFCA 2.0 should pursue the reduction of losses not merely as a last step of the project, but as the overarching goal, which requires implementation competence throughout the course of the project.

In 1936, the German iron and steel industry researched the idea of material balances with regard to losses and their sources (Rummel, 1936). Rummel (1936) suggests identifying the most significant influencing factors of the material flows in order to systematize the analyses, ultimately leading to better decisions, for example, with regard to production materials, methods and machines. Moreover, the article addresses the topic of cooperation between a business economist and a production engineer. Such a cooperation requires mutual trust because otherwise, they will reap "stalks without ears"[36] (Rummel, 1936, p. 228). This image can be applied to the method of MFCA 2.0 by interpreting the stalks as the identification of the improvement potentials and the ears as the realization of them. The idea of mutual trust is an element that should not be underestimated within the consultant team and with regard to the cooperation of the consultants with the client company since the application of MFCA 2.0 and in particular the implementation of measures requires trust. If an MFCA project ends with the evaluation of different improvement measures and lacks implementation competence, a decisive step in the application of the method is missing, hence undermining the method's effectiveness. Taking up the image from above, an MFCA project that lacks the implementation of measures represents "stalks without ears" (Rummel, 1936, p. 228).

Once the consultant team has been found and formed, it is their task to apply the method with their methodical, technical and implementation competence. A successful MFCA 2.0 consulting project ends with the implementation of the improvement measures that were developed and selected.

[35] Own translation, original in German: "Rationalisierungsmöglichkeiten zu erkennen" (Kilger et al., 2012, p. 252)
[36] Own translation, original in German: "Halme ohne Ähren" (Rummel, 1936, p. 228)

5.4 Approaches to Finding Adequate, Eco-Efficient, and Eco-Effective Improvement Measures

The application of MFCA 2.0 should lead to the assessment, choice and implementation of measures. This section will examine the question of how to find adequate, eco-efficient and eco-effective measures. Following the approach of process consulting, the idea is that there is a large amount of expertise available in the company. This expertise can be used to generate ideas for loss-reducing improvement measures that increase the efficiency of the process under analysis. In this context, material losses are interpreted as a problem and improvement measures that reduce these losses as potential solutions. The following paragraph is going to explain how to get to a potential solution.

5.4.1 Defining the Problem and Its Framework Conditions

Improvement measures can be developed in two ways. The first one presupposes that the company already has a tangible idea for an improvement measure that can reduce a specific material loss. The purpose of the consulting assignment is to evaluate this option and to quantify the saving potentials for the system under analysis from a physical, economic and environmental perspective. The second way is based on the intention of the company to increase its production efficiency by reducing its material losses. The company may have heard of the method of MFCA, but awareness of losses and ideas for improvement measures are rather limited or not yet existent. While the first way follows a clear path of the consulting project, the second way requires more effort and analytical tasks at the beginning of the consulting project to develop ideas for improvement measures that are to be evaluated. However, it is important to understand that these two ways are not mutually exclusive. Quite the contrary, their combination can enrich an MFCA project, and it is an attribute of successful consulting based on MFCA 2.0 if these two ways are pursued at the same time. In a consulting situation, it is a consultant’s task to enquire—in consultation with the client company—whether improvement suggestions are present already and whether they have or should be followed up by further analyses (Ellebracht et al., 2018). Generally, the knowledge and experience of a company’s employees are prerequisites for high-quality suggestions. These can be encouraged with a positive, welcoming attitude, which in turn creates an innovation-friendly atmosphere (Patzak, 1982).

Two things are of high importance in order to find an adequate improvement measure (Ellebracht et al., 2018). The first aspect of high importance is the understanding of the system under analysis in a way that reveals the boundary conditions surrounding the occurrence of the material loss(es) (Patzak, 1982). Once these boundary conditions have been identified, the next question is which of these conditions are unchangeable in order to narrow down the scope of action for improvement measures. Patzak (1982) gives two examples of a certain material that cannot be replaced and a maximum investment sum that must not be passed. When working out the unchangeable boundary conditions, caution and a good amount of skepticism should be exercised because it is human to classify a specific boundary condition as unchangeable rather than to question its immutability. Therefore, an inversed approach is suggested, which at first assumes that all boundary conditions are changeable. Starting from this initial assumption, the project team or the persons involved can discuss and decide which of these conditions are unchangeable (Patzak, 1982). Once the unchangeable conditions have been determined, their sum constitutes the system environment and the consequent system boundaries that should be respected in the search for improvement measures. The following list can be used as guidance when identifying and structuring the environment (Patzak, 1982, p. 148, own translation from German):

1. Natural environment
   1.1. Aspects of living nature (human factors, flora, fauna, natural resources)
   1.2. Aspects of inanimate nature (climate, surroundings, also natural resources)
2. Artificial environment (created by humans)
   2.1. Technical aspects (technical systems, state of knowledge, technology, norms, standards)
   2.2. Economic aspects (microeconomic factors of a company: budget, strategy, know-how etc.) and macroeconomic factors (procurement markets, sales markets, customs duties and charges etc.)
   2.3. Legal and political aspects (laws, public institutions, political circumstances)
   2.4. Socio-cultural aspects (demographic and cultural development, living standard etc.)

This method requires an impartial attitude particularly at the beginning of the search for improvement measures, and it can lead to a redefinition of the problem. If a problem has not been sufficiently and precisely defined, it may undermine the effectiveness of the project (Turner, 1982). The following quote summarizes how to search for improvement measures:

> A largely defined problem is already half solved; the real achievement in problem solving is to formulate a problem productively. [...] It is rarely taught how to discover and define problems. Since mere logical thinking to begin with is purely destructive, this alone cannot promote the ability to see and formulate problems. (Patzak, 1982, p. 163, own translation from German)

Additionally, the cause(s) of the material loss(es) should be identified, and it is important to differentiate symptom(s) from their cause(s) so that the improvement measure is effective, addressing the problem at its roots. It is a matter of time until a solution that only addresses symptoms is going to demand rework and hence also additional effort and cost.

Holistic and goal-oriented human thinking that strives for improvements can be divided in two stages. The first stage comprises synthesis and the second stage comprises analysis (Patzak, 1982). Synthesis and analysis are different stages that are nonetheless mutually dependent and interrelated, and that is one reason why they complement each other. The meaning of the term *synthesis* is to combine often diverse parts or elements in a way that they lead to a new whole (Merriam-Webster, 2024). In chemistry, *synthesis* means that chemical elements, groups or compounds either produce a new substance through their union or through the degradation of a compound of higher complexity (Merriam-Webster, 2024). In systems thinking, *synthesis* is a creative activity that allows to try things out with heuristic methods and rules of thumb (Patzak, 1982). It seeks to find unknown properties of the objects under study, assuming that there is an unknown number of solutions that can be explored. Synthesis has an artistic character, hence welcoming and fostering innovative ideas (Patzak, 1982). It offers methods fostering thinking outside the box such as creating relationships and links but also confronting properties in order to develop new ideas. Therefore, every solution option is based on present conditions, knowledge and ideas that are reevaluated with regard to the present problem. When discussing this subject, Patzak (1982) builds on Koestler (1981) who coined the term *bisociation*:

> The history of science is a history of marriages between ideas which were previously strangers to each other, and frequently considered incompatible. […] This act of cross-fertilization—or self-fertilization within a single brain—seems to be the essence of creativity. I have proposed for it the term *bisociation.* (Koestler, 1981, p. 2)

There are three innovative approaches on how to solve a problem (Patzak, 1982). The first approach is intuitive and uses the trial-and-error method. Over time, an appropriate solution can be developed with this approach. The scientific transposition of knowledge from one discipline to another is a second path to possible solutions. Abrupt rearrangement is an example for such a transposition. A third option approaches the problem in a discursive way, thus incrementally developing a solution. Although these approaches allow many degrees of freedom, none of them can guarantee the finding of a suitable solution (Patzak, 1982). In the synthesis stage, bureaucratic tasks should be avoided because they imply prescribed orders and procedures which are not always expedient, thereby hampering innovative thinking processes. While solution-oriented thinking can certainly be supported, a sudden insight may lead to a so-called *eureka moment* (Patzak, 1982). Finally, the following three pieces of advice are noteworthy (Patzak, 1982):

1. Do not think of solutions that have worked in the past. Instead, adopt an ideal image and deviate from it based on details, thus shaping a realistic version of the image.
2. Do not limit on one solution only. Instead, develop several solution options and then, make a choice. Take into consideration that solution options can also be combined, potentially leading to a total saving potential that is larger than the sum of the individual saving potentials of the options due to secondary effects.
3. Do not evaluate, criticize or judge too early. These are analytical steps and they should be taken later in the analysis stage.

5.4.2 The Search for Solutions

The synthesis stage can be supported by a suggestion scheme, which enables employees to easily submit suggestions for improvement measures. The topic of the suggestion scheme will be discussed later on in this subsection in more detail.

The synthesis stage is followed by the analysis stage, which comprises a more technical approach by reviewing and evaluating the results of the synthesis stage (Patzak, 1982). It is characterized as technical, exact and logical, using different methods of mathematics and of natural sciences (Patzak, 1982). In this stage, promising measures can already be implemented on an experimental level to gain a better understanding of their effects and to develop necessary adjustments based on practical experiences (Turner, 1982).

For a successful consulting project, the project team should be diverse in the sense that it is composed of people with different specialist backgrounds. For example, Patzak (1982) advises against the involvement of many technical specialists. Although it may seem counter-intuitive to limit the number of persons with a technical background, this limitation makes room for persons with different backgrounds such as persons fulfilling administrative functions that add a different perspective. The individual background is not as important as the argument of a new perspective (Patzak, 1982). Moreover, especially individuals who strive for perfection should be selected sparingly since this characteristic can hamper creative powers and the exploration of new paths (Patzak, 1982). Once the stages synthesis and analysis have been completed, decision-making follows in the third stage. This step comprises a selective choice and it factors in the acceptability of the different options under consideration (Patzak, 1982).

Taking up the topic of a suggestion scheme again, such a scheme can document and store all the suggestions that have been made, so that they can be accessed and reviewed again at a later time (Patzak, 1982). A suggestion scheme is also relevant for continuous improvement based on MFCA 2.0 (cf. Section 5.5). To fill a suggestion scheme with suggestions, creativity is needed, and creativity, in turn, is the result of the three components creative-thinking skills, expertise and motivation (Amabile, 1998). Therefore, in addition to a new, inventive approach to an existing problem, creativity requires expertise and motivation (Amabile, 1998). Motivation is a critical factor that can be encouraged by a suggestion scheme, among others, since it offers a practicable way to formulate and communicate an improvement suggestion. When fostering creativity, it is important to decidedly welcome every suggestion for improvement at the outset and to reward suggestions per se because when searching for solutions, it is oftentimes useful to learn as well which of the suggestions are useful and which are not (Amabile, 1998). Although this process of differentiation is important, it can be counterproductive if started too early. Neagoe and Mărăscu Klein (2009) confirm that an employee suggestion system is a useful tool that motivates employees to use their creative skills to initiate and foster improvement processes as a bottom-up approach, and the authors formulate tangible recommendations. Their approach originates from the Japanese concept of *Kaizen Teian*, which the following Section 5.5 will address in more detail with regard to continuous improvement (Bertagnolli, 2018; Japan Human Relations Association, 1997; Neagoe & Mărăscu Klein, 2009).

Consequently, when applying MFCA 2.0, it is advisable to establish a suggestion scheme. The submitted suggestions can then be reviewed and assessed regarding the saving potential they entail, respectively. Since MFCA 2.0 assesses improvement measures with a scenario-based approach considering the whole system under analysis, the saving potential may be larger than initially assumed, which can function as a game changer in management decisions.

5.4.3 Different Kinds of Improvements in the Literature

Improvement measures can be divided into three categories: technical, organizational and behavioral. Examples for technical measures are changes in machine equipment or aspects relating to material and energy supply and inputs. Organizational measures can be policies, standards or process changes. Measures addressing human behavior are, for example, special training programs that lead to new skills or awareness-raising activities leading to changes of attitudes or certain habits over time. Incentive systems are worth considering with regard to behavioral measures since human behavior is rather rigid and shaped by habits and routines. Additionally, loss-reducing improvement measures that are a result of an MFCA analysis can be divided into two categories (Nakajima, 2010, p. 48):

- Improvement support and improvement investment support
- Process design support and capital investment support

The first category comprises support regarding on-site improvement measures and the resulting financial aspects regarding investment and cost savings (Nakajima, 2010). The second category aims at losses that cannot be reduced on-site and therefore require changes in the production process. These changes result from modifications in the process design and in product specifications, which moreover require capital investments (Nakajima, 2010). Nakajima (2010) emphasizes that both improvement categories foster the reduction of environmental impacts and that the MFCA method fosters sustainable manufacturing.

In the literature, specific and practical support in the search for improvement measures can be found. In the standard VDI 4800 Part 1 on the topic of resource efficiency, The Association of German Engineers (VDI) points out 37 strategies that increase resource efficiency (VDI, 2016). The following strategies explicitly address the issue of losses occurring in production processes. They are therefore useful signposts in the search for appropriate improvement measures (VDI, 2016, p. 39):

- 20 Minimisation of planned loss
- 21 Minimisation of planned scrap
- 22 Avoidance of losses due to rework
- 23 Avoidance of losses due to disposal of finished products
- 24 Avoidance of losses due to disposal of purchased materials
- 25 Avoidance of losses due to improper storage or obsolescence
- 28 Use of process heat and waste heat
- 33 Cascading use of auxiliary materials and operating supplies

The list contains various kinds of losses such as scrap and rework, and it also addresses energy losses in the form of heat. Moreover, the standard differentiates *planned* losses from *unplanned* losses. While the former result from certain conditions related to the product or process design, the latter appear when materials or objects are stored for too long or under inadequate conditions.

The Japanese management philosophy lean management offers many points of reference for the methodological advancement of MFCA. The Japanese term *muda* means to make a fruitless effort, and it thus has a negative connotation (Bertagnolli, 2018). It is usually translated as “waste” and Bertagnolli (2018) argues that this falls short of the meaning of *muda* in Japanese since the term implies human labor that does not generate additional value and should therefore be avoided. Lean management defines seven kinds of *muda* (Ohno, 2013):

- Overproduction
- Motion
- Waiting
- Transport
- Over-processing
- Inventory
- Defects

Bertagnolli (2018) introduces “skills” as the eighth kind of muda and argues that it is the waste of knowledge and abilities of a company’s employees that remain unused. This is food for thought with regard to MFCA 2.0 because it confirms the hypothesis that ideas for improvement measures are already existent within the company. The method’s full potential can only be realized if the corporate employees and their ideas are invited and integrated in the project.

Furthermore, there is a two-part standard on lean management numbered 2870 by the Association of German Engineers (VDI, 2012, 2013). Part two of the standard contains a list of methods and tools that support the implementation of lean production systems (VDI, 2013). It also contains a list of 35 methods that are evaluated with regard to quality, cost and time. Moreover, the methods are sorted by several principles, one of these principles being the avoidance of waste. The standard suggests the following four methods to implement this principle:

- Chaku Chaku (Japanese for “load load”):

  If paths between workstations are minimized, processing steps are simplified and processing times reduced.
- Low-cost automation:

  This method focuses on processes that support operations without much additional effort or cost, oftentimes taking advantage of physical laws such as gravity.
- Total productive maintenance:

  Service and maintenance work, including preventive maintenance, are practiced by the employees working with the objects that are to be maintained.
- Waste analysis:

  The reduction of non-value-adding production steps and activities is an effective method to increase resource efficiency.

The VDI standard 2870 contains additional information on supplementary methods and supporting tools, while also pointing out risks and recommending further literature on the different methods.

Another useful reference is the TRIZ method, which was coined by Altshuller mainly in the 1960s in the Soviet Union (Lerner, 1991). TRIZ is a Russian acronym meaning “The Theory of Solving Inventive Problems” (TIPS) in English (Lerner, 1991). The main idea is that every technical problem is a contradiction that can be overcome with one or multiple of the 40 principles TRIZ offers (Altshuller, 2002). These principles are the result of Altshuller’s research on 200,000 patents, and he derived an algorithm that describes how to develop creative solutions for complex problems (Altshuller, 2002). Two examples for such principles are asymmetry and nesting, and these two can offer multiple advantages: The principle of asymmetry means to replace symmetrical forms with asymmetrical ones or to increase the asymmetry of a form. The principle of nesting places objects inside another object, and this principle is also present in the Russian set of dolls called Matrioshka (Altshuller, 2002). In order to develop an appropriate solution, TRIZ first abstracts the problem, then analyzes it against the background of the different TRIZ principles and finally specifies it based on one or multiple principle(s) (Altshuller, 2002). When searching for adequate measures that realize the improvement potentials based on material losses and quantified with MFCA 2.0, considering the TRIZ principles can provide valuable food for thought. In the introduction to the book authored by Altshuller, Shulyak formulated the thought that once a principle has been identified as helpful and a solution has been developed, the implementation of this improvement measure remains an important task to be completed by engineers.

With regard to MFCA 2.0, as pointed out above, an improvement measure will not develop its potential until it has been implemented in practice. Therefore, once ideas for improvement measures have been developed and evaluated following the synthesis and analysis stages, the next step is to make a conscious decision for one or multiple improvement opportunities before their implementation.

5.4.4 Implementation of Improvement Measures

When implementing improvement measures, it is important to understand that measures which are partly, poorly or not implementable at all for certain reasons represent an additional loss (Turner, 1982). This loss in the form of time, money and effort should be avoided from the outset, just like the MFCA method strives to reduce material losses and the inefficiencies resulting from them. To increase the chances of a lasting impact of the improvement measures selected within a consulting relationship, the following ideas are worth considering. First, the implementation stage should not be seen as separate from the other stages. Instead, it should be initiated as early as possible because it also comprises preparatory measures, as will be explained in the following paragraphs. Moreover, when selecting and implementing a measure, it is important to bear in mind that there may be different groups of persons or departments within the company that can be held responsible. Therefore, Nakajima (2010) sees a problem in the circumstance that the persons responsible for the occurrence of material losses are usually not the persons responsible for the management decision to implement the corresponding improvement measure. Although no specific solution was proposed in the paper, the researcher states that this was the decisive factor for the successful implementation of improvement measures (Nakajima, 2010).

Acceptance of improvement measures among the employees should also be kept in mind when searching for measures. It can be increased through early announcements and continuous communication (Turner, 1982). Interviews with employees of different departments are a powerful way for the consultant to gain a deeper understanding of the company (Turner, 1982). Since it enables communication on a personal level, it fosters trust and acceptance (Turner, 1982). The work to convince of certain improvement measures should preferably take place in dialogue formats and not in the form of written texts such as project reports (Turner, 1982). Since dialogue formats usually offer room for questions and contingencies, they increase acceptance and generate an atmosphere that is open for feedback. These advantages increase the chances of support and commitment of the employees, thus securing the impact of the measure(s). At this stage in the project, it is important to hear and process the feedback to adapt the measures correspondingly where applicable. Moreover, an experienced and skilled consultant can detect and read information between the lines that can indicate a skeptical position or critical views, which the consultant can then address explicitly or implicitly. Feedback is an integral part of a successful MFCA 2.0 project, and the consultant should periodically review acceptance and support regarding the measures to be implemented. In rare cases, discarding or replacing an improvement measure in default of acceptance and support can be necessary as a last resort (Turner, 1982). Although such cases are rare, they demonstrate that the measure that ranks highest regarding financial and GHG emissions-based savings is not automatically the best option regarding implementation and effectiveness in practice. Generally, an open and regular communication policy including measures like interviews is an important success factor and a tool that empowers a company and its employees on the road towards eco-efficient and eco-effective improvement measures.

Taking up the approach of the ISO 14052, which covers the implementation of the method in a supply chain (ISO, 2017), the application of the method MFCA 2.0 does not need to and should not end at the company boundaries such as the factory gate. Similar to the aforementioned ISO standard, MFCA 2.0 suggests looking beyond the process boundaries and considering the cooperation with relevant stakeholders to increase overall resource efficiency. Case studies show that improvement potentials can, for example, result from oversized buffers and unused recycling or cascading opportunities (METI, 2011). Moreover, the view beyond the process boundaries and factory gates increases transparency and thus offers new insights when localizing and quantifying material losses, even though it may not immediately lead to a reduction of these.

5.4.5 Conclusion: How to Search for Improvement Measures

Although there is no guarantee that MFCA 2.0 leads to adequate, eco-efficient and eco-effective measures, there is practical advice to be followed and goal-oriented steps to be taken. These were pointed out and described in this section. The search for adequate, eco-efficient and eco-effective improvement measures can benefit from systems thinking, which first demands an accurate description of the current situation. In a second step, creativity is required, which can be stimulated with specific literature containing strategies and methods that were introduced and cited above. The improvement ideas that were developed during these activities can then be collected in a suggestion scheme. Once a decision for one or multiple measures based on the MFCA 2.0 calculation results and employee feedback has been taken, the next step represents their implementation in cooperation with the employees. MFCA 2.0 should also broaden the view beyond the factory gates, thus paving the way for the application of MFCA 2.0 in cooperation with other companies along the supply chain.

5.5 Continuous Use of MFCA 2.0: Improvement in Small Steps

In addition to a time-limited consulting project, MFCA 2.0 can be implemented for continuous improvement. In the English language, continuous improvement is known as "continuous improvement process" (CIP), and in the German language, it is known as "kontinuierlicher Verbesserungsprozess" (KVP).

5.5.1 The Framework Conditions and Incentives for Continuous Improvement

Both CIP and KVP follow the PDCA cycle, which represents a step-by-step guideline for continuous improvement and problem solving. The PDCA cycle was developed by Deming and published in 1986 as a management method for quality management. The continuous use of MFCA 2.0 can be pursued in combination with or independently from a previous consulting project. If a consultant was employed, a company should involve its employees to a high degree so that they experience and understand how the method approaches material losses. In this way, the consulting project initiates a change in awareness of material losses, the corresponding improvement potentials and improvement measures. This integrates the method in the company so that material losses are gradually reduced after a time-limited consulting project.

When implementing MFCA 2.0 as a method for continuous improvement, it is important to keep in mind that there may be different persons, groups of persons or departments involved, which can have different responsibilities and conflicting goals (Nakajima, 2010). For example, one department's interest may be in reducing material losses, while the interest of management may be to avoid large investments, which an improvement measure may require. Therefore, responsibilities and incentives should be reviewed and aligned in light of MFCA 2.0 in order to avoid competing interests within the company.

Moreover, continuous improvement can be pursued by the cost accounting department, which tracks cost variances and unplanned cost increases in particular. Kilger (1993) already posed the question of how employees can be motivated to avoid unplanned cost increases, and he presented different ideas and arguments. The first step is to quantify cost variances, and the second step is to communicate the variances and their reasons to the responsible persons (Kilger, 1993). The third step comprises a financial reward, which increases cost awareness and represents an incentive to reduce costs. However, Kilger (1993) opposes, such a step carries the risk of a bad working atmosphere. He cites Hasenack who already pointed out in an article which was published 1929/1930 that this step can start a blame game, i.e., costs are passed on and arguments are searched why the cause for a cost increase lies within another cost center. Scholar Käfer (1964) agrees to this reasoning. Moreover, cost center managers are tempted to intentionally increase the amount of their cost specifications in order to make room for improvement, taking effect at a later time (Kilger, 1993). Nevertheless, saving potentials will be realized and thus naturally decrease over time, which will also reduce the incentive (Kilger, 1993). Despite these risks and reasons, there are sources stating that this kind of financial incentives was popular in the US in the past (Henrici, 1960; Matz, 1964). Against the background of today's profit-maximizing economic dynamics, this line of argument should be reconsidered.

MFCA 2.0 focuses on the quantification of improvement potentials, and it enables a broader view than the mere quantification of losses. If losses are shifted within the company or even the supply chain, the resource efficiency of the process under analysis is not going to improve. In order to be continuously and successfully used, MFCA 2.0 suggests a different incentive scheme. Financial incentives are more effective and useful when it comes to individual material-based tasks executed by single employees since this kind of incentive has a low risk of the mentioned unintended side effects (Kilger, 1993). Since the documentation effort for individual employees is rather high, Kilger (1993) suggests acquiring the data for the different teams, respectively. Although Kilger (1993) himself weakens his suggestion since the whole team gets credit for individual efforts, there are strong arguments in favor of this scope of application. First, the approach of MFCA 2.0 with its focus on resource efficiency improvements is holistic and does not pursue a selective application. Second, with regard to today's high importance of teamwork, the cooperative and team-based approach to the search and implementation of improvement measures represents a second strong argument.

Cost variances that were detected by the cost accounting department can be divided in two categories: cost variances caused by employees and cost variances which they did not cause (Kilger, 1993). While one goal is to avoid cost variances, another goal is to reduce the costs below the planned costs. This can be mirrored in financial rewards that are designed degressively, i.e., the first Euro that gets reduced is rewarded higher than the following Euros (Kilger, 1993). As a result, small improvements are not less attractive with regard to the financial reward scheme than large improvements, which oftentimes require more time and investment. This is an important aspect that supports the continuous use of MFCA 2.0. The long-term application of the method requires sequential improvements, which are easier to implement in small steps and parallel to ongoing operations.

The Japan Human Relations Association (1997) emphasizes that every single improvement suggestion should be appreciated with a minimum amount of money as a reward in order to encourage the continuous lookout for improvements. Even if an improvement leads to small savings only, these also represent contributions to continuous improvement.

5.5.2 *Improvement Using Kaizen and Kaikaku*

The Japanese approach to continuous improvement is *Kaizen* and it will be explained in the following (Bertagnolli, 2018; Japan Human Relations Association, 1997). It is expressed with the following two Japanese characters depicted in Figure 56, and it can be translated as "change for the better" (Bertagnolli, 2018, p. 152, own translation from German[37]).

Figure 56: Japanese characters for Kaizen (Bertagnolli, 2018, p. 152)

改 善

Kaizen can be understood as management approach and as a new approach to corporate culture (Heß, 1995). What speaks for a management approach is its application as a management tool. However, Heß (1995) remarks, Kaizen requires more than the management's commitment. Therefore, the interpretation of Kaizen as cultural approach ascribes a lot of influence to a company's employees (Heß, 1995). Instead of suggesting a predefined path to a solution, the Kaizen approach assumes that improvements require specific company-internal knowledge that can be accessed and activated through the company's employees. This encourages and also demands the employees' mental abilities to identify improvement potentials and to develop suitable measures without management instructions "from above". Hence, Kaizen represents a cultural approach to continuous improvement. In an analogous manner, *Kaizen costing* is a costing tool to reduce costs through efficiency increases in small incremental steps (Drury, 2012). It can be used in the manufacturing stage of a product's life cycle, and the employees play a decisive role as well (Drury, 2012).

Originally, Kaizen was designed in Japan as a philosophy that empowers a company's employees to optimize all kinds of processes they face throughout their day-to-day work (Bertagnolli, 2018). Kaizen does not intend to add continuous improvement as an additional task or add-on to established practice (Bertagnolli, 2018). In Japan, the Kaizen philosophy is supposed to take 75 min per week, and it is relevant to all areas of life including professional, social and private areas (Bertagnolli, 2018). However, Bertagnolli (2018) remarks, this holistic and philosophical understanding of the term is oftentimes lacking when it gets applied in countries and cultures outside of Japan. Although the time specification may seem like an additional inefficiency in the first instance, it is important to understand that Kaizen is an investment which pays out over time. In that regard, it is important to evaluate effort and gain of each improvement suggestion concerning time, money and space requirements to avoid disimprovements (Bertagnolli, 2018). Additionally, GHG emissions-related saving potentials as a result of the MFCA 2.0 approach can be added as ecological criterion. In value stream mapping—a visual method of lean management—material inefficiencies and, if possible, their causes are identified and marked with a *Kaizen flash*. A Kaizen flash is a cloud-shaped, red-colored symbol. It is combined with keywords that describe inefficiencies and—in case they are available—their causes as well as ideas for possible solutions (Bertagnolli, 2018).

In summary, Kaizen is a philosophy that enables the pursuit of many kinds of improvement in small steps. It empowers a company's employees because the Kaizen approach allows them to

[37] Own translation, original in German: "Kaizen setzt sich aus den beiden japanischen Begriffen „Kai“ für Veränderung [sic] und „Zen“ für „zum Guten“ oder „zum Besseren“ zusammen." (Bertagnolli, 2018, p. 152)

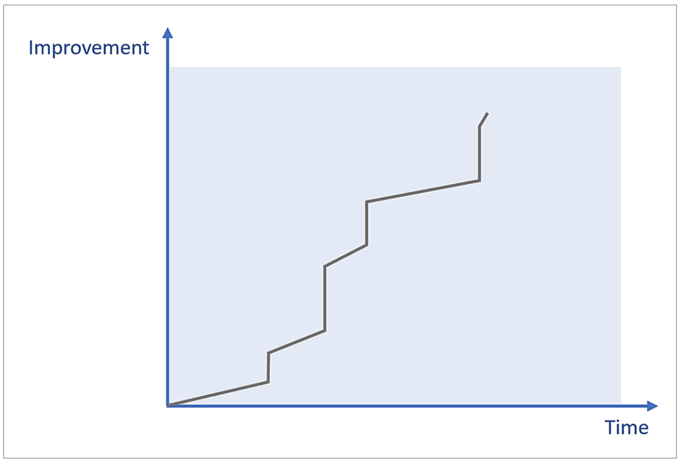
evaluate and suggest these improvements themselves. Even though the appointment of Kaizen experts—just like lean experts—are a measure undertaken by many companies, the final goal should be their redundancy (Bertagnolli, 2018). Once the Kaizen experts have taught the method to the other employees, their work is not required on a daily basis anymore. The employees now carry forward these ideas themselves.

Kaikaku, another concept borrowed from lean management, stands in contrast to Kaizen because it does not pursue continuous improvement over time (Bertagnolli, 2018). Kaikaku means "radical change" and it pursues larger improvements by questioning the status quo, thus fostering innovations (Bertagnolli, 2018). Instead of continuous improvement in small steps as pursued by Kaizen, Kaikaku pursues fundamental changes such as the redesign of existing processes or the introduction of new processes, which usually require high technologies and corresponding experts (Bertagnolli, 2018).

A combination of Kaikaku and Kaizen is useful because the two concepts complement and mutually enforce each other, as the following

Figure 57 illustrates:

Figure 57: Visualization of Kaizen and Kaikaku over time in a two-dimensional diagram (Adapted from Bertagnolli, 2018, p. 156 and Imai, 2001, p. 61)



5.5.3 *Continuous Improvement With MFCA 2.0 in Practice*

When implementing MFCA 2.0 as continuous improvement process, it may appear useful to measure its effects in the form of an improvement indicator. However, just like Kaizen represents a philosophy, MFCA 2.0 represents a tool to increase resource efficiency that cannot be reduced to a figure. Following Bertagnolli's (2018) advice, measuring improvements within a specified period, defining targets that quantify minimum improvements or a number of improvement suggestions for a specified period will not carry the method's application in the long run. Instead, they will put the employees under pressure and impede the search for creative solutions. The fear of possible consequences in case the targets are not achieved will intensify the pressure, hence further impairing the method's intention. If this advice is considered, MFCA 2.0 can facilitate client learning, which Turner (1982) defined as additional goal of consulting. The company becomes more receptive to change, thus developing into a learning organization that pursues the goal of resource efficiency.

There are decisive factors for the usage of MFCA 2.0 in a corporate context in the long run. The following factors were borrowed from the history of cost accounting, and they explain why different forms of cost accounting developed over time (Kilger, 1993). Since cost accounting and MFCA 2.0 have many parallels, these reasons are transferrable to the implementation of MFCA 2.0 in a specific corporate context.

First, corporate management decides what requirements the cost accounting method should fulfill and what functions it should have (A. Müller, 1935/36). Over time, the focus of cost accounting has shifted from the analysis of data from the past towards the purpose of cost planning (Kilger, 1993). With regard to MFCA 2.0, it is important for corporate management to actively participate in the customization of the method so that its results are meaningful and find management support in the long run. Furthermore, it should be ensured that MFCA 2.0 strives for actual improvements in resource efficiency. MFCA 2.0 does not strive for the mere analysis of data from the past, even though this data provides a necessary basis.

Second, the method of cost accounting should be supported with computer software. The specific form of a cost accounting method depends on the software available on the market (Kilger, 1993). Moreover, the further development of cost accounting was driven by the advancement and dissemination of corresponding software (Kilger, 1993). MFCA 2.0 with its new algorithms is a powerful and effective tool for resource efficiency, and due to the great number of calculations necessary for the scenario-based approach, it also requires software support to be continuously implemented. *Umberto 11®* is an example for the implementation of the method's algorithms, as explained in Sections 4.1 and 4.3.

Third, in addition to the two previous factors, the level of knowledge and education of a company's employees influences in what way the method is implemented (Kilger, 1993). A certain level of knowledge and education are required to understand and apply a method correctly. It is the result of business education and experience (Kilger, 1993). MFCA 2.0 can be learned through training and experience, and these two factors are also going to influence the method's success in the long run. The employees need to understand the purpose and usage of the method to acquire the skills to apply the method as intended. In this way, they will make the company's processes more resource efficient.

Finally, the choice for a specific cost accounting practice needs to consider a company's individual structure including its production processes (Kilger, 1993). If a company's structure is complex because its processes are multi-layered and interwoven, cost accounting practice should reflect these specifications (Kilger, 1993). In this way, cost accounting is able to fulfill its purpose to display the company's structure and its processes (Kilger, 1993). This applies to MFCA 2.0 as well. MFCA 2.0 needs to take the company-specific circumstances into account to deliver useful information. At this stage, simplifications and shortcuts are resource-efficiency measures implemented in a place that is not ideal. For example, the sublimation of several production steps in one quantity center should be done with caution since it also reduces the level of detail in the results. It will prove worthwhile to invest more time and effort in the beginning when implementing the method because the implementation based on the individual corporate structure will lead to differentiated results. These results provide a solid basis for continuous improvement.

5.6 MFCA 2.0 Data

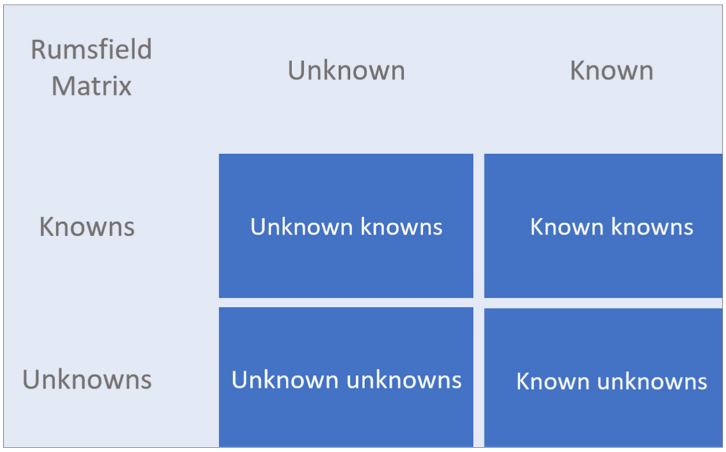
Data is an essential element in an MFCA analysis, and its collection should not be underestimated. Data acquisition can be time-consuming since the data an MFCA requires is usually non-existent in a company. Therefore, data collection represents the first step in consulting. It means to provide the client with information (Turner, 1982). Although the topic of data collection may seem self-evident, it is important for a company to understand the value of the data acquisition for the following MFCA analysis.

It may seem sensible to use data that is already available in a merchandise management system. However, this is the dichotomy of MFCA data: Data is available from the corporate data system, but it is not sufficient for an MFCA analysis. While certain data such as product quantities, purchase volumes and cost factors in the form of purchase prices can be used, material losses and energy consumption rates should be recorded or at least verified before they are used in the MFCA analysis. Kokubu and Kitada (2015) describe this as "the losses that have been newly 'invented' by MFCA" (p. 1282). Therefore, the consultant and other responsible persons—depending on the specific MFCA implementation design—should request the acquisition of new data within the MFCA project. Due to its focus on losses, MFCA looks under the surface and requires data which usual corporate practice does not demand. In the case that loss data is already existent, it still bears the risk that this data was entered in the data collection system in a different context, due to a different incentive and with a different purpose. Furthermore, the survey period and age of the data should be enquired critically. These aspects could distort the MFCA results and undermine the plausibility and consequently the effectiveness of the method. An example is the documentation of rejects, which is sometimes not entered truthfully due to financial incentives like bonus payments for the achievement of quality targets. If this reject rate is used for the MFCA project, measures that could effectively avoid these undocumented rejects could be missed chances to increase the resource efficiency of these production processes.

Almost one hundred years ago, Haas (1927) emphasized in his presentation on standard costing (cf. Paragraph 2.2.1.3) that historical data is not expedient for cost accounting with a future-oriented purpose. Therefore, he argues, in order to generate calculation results that are of relevance for the future, the used data should be up-to-date (Haas, 1927). This also applies to MFCA data. In order to get relevant MFCA results, the used data should be as new as possible. MFCA 2.0 can provide a basis for future recommendations and decisions. However, the quality highly depends on the data quality and the age of the data.

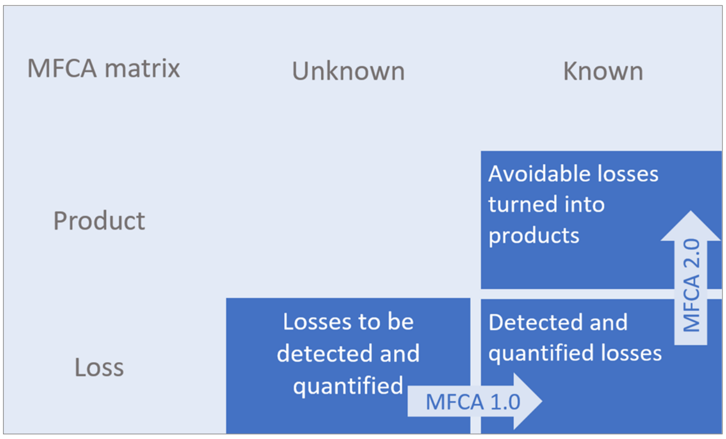
The following thoughts originate from the field of philosophy, and they explain how MFCA 2.0 approaches the topic of data. Just like cutting-edge research breaks new ground with its findings, MFCA 2.0 pursues data on unknown terrain. The data on material losses was not included in the data collection so far. In his book *Ignorance: How It Drives Science*, Firestein (2012) argues that new scientific discoveries can be made if research activities pursue research fields that lie beyond the facts that are already known. The term *epistemology* describes a philosophical branch that focuses on knowledge and it aims to answer the question of how knowledge can be acquired. As the US-American secretary of defense Rumsfield phrased in a speech in 2002, there are *known knowns*, *known unknowns*, and *unknown unknowns* (Rumsfield, 2002, cited after Shermer, 2012). The idea of this phrase was later used to create the so-called *Rumsfield Matrix*, which is depicted in Figure 58 (Krogerus & Tschäppeler, 2011).

Figure 58: The Rumsfield Matrix and its application to MFCA 2.0 (Adapted from Krogerus & Tschäppeler, 2011)



This principle is helpful to understand how MFCA 2.0 approaches the meaning of data. At the beginning of an MFCA 2.0 project, the data required for further analysis is usually unknown, i.e., the values of material losses are not available. Therefore, the first step is to understand and accept that there are unknown losses. The next step is to make these unknown losses known through measurement and data collection. Once the losses have been detected, quantified and made transparent in this way, the scenario-based algorithms of MFCA 2.0 can quantify the saving potentials based on these losses. An improvement measure can partly or completely reduce the losses, which the two categories *avoidable losses* and *unavoidable losses* represent. Avoidable and known losses can be shifted from *loss* to the category *product*. Thereby, the overall resource efficiency of the process under analysis can be increased. Figure 59 summarizes this line of argument and illustrates how unknown losses can be turned into additional products.

Figure 59: MFCA matrix based on the idea of the Rumsfield Matrix (Own illustration)



The standard ISO 14051 contains further useful information and requirements on the topic of data (ISO, 2011). First, the standard explains that data about material losses is not easily accessible—if at all—through existing environmental management information or accounting systems (ISO, 2011). Therefore, the total value of the losses is unknown. As a consequence, ideas on how to increase the resource efficiency of the processes are of little relevance, and economic and GHG-based saving potentials remain unused (ISO, 2011). Second, the data being collected should be accurate, complete and comparable (ISO, 2011). Moreover, the measuring units should be chosen not only with regard to these requirements concerning data quality, but also with regard to their usability for environmental assessments (ISO, 2011). For example, material-based emission factors are measured in CO_2e/kg, meaning that they require a weight specification of the material under analysis. Third, when collecting data, it is important to define a time period that includes fluctuations of the processes such as seasonal fluctuations (ISO, 2011). Depending on the specific situation such as industry-specific practices, the data collection period can vary between one month and one year, and it can also cover a production batch (ISO, 2011). If this quality requirement is not ensured, the results of the MFCA analysis might not be applicable to the actual situation. This would not only pose a serious risk to the implementation of the method, but also to the method's reputation and hence the probability of applying it again in the future. Fourth, the determination of the costs for the specific quantity centers should in any case be preferred over cost allocation processes, which require estimations and approximations that are often imprecise (ISO, 2011). However, the norm states, cost data for energy, system and waste management is in practice not available for the quantity centers defined in the MFCA analysis. Hence, the data that is usually available for a process chain or a plant requires the allocation to the quantity center in a first step. In a second step, these results are allocated to the outputs of the (intermediate) products and losses, respectively. Fifth, pursuing a long-term application of the MFCA method, the norm comprises the following recommendations. When carrying out an MFCA analysis, ideas on how to improve the implementation of the method in general and the data collection processes in particular can be documented simultaneously (ISO, 2011). If these suggestions are followed, the implementation of the method can gradually be improved over time. An example is the automatization of the data collection, leading to more precise data and less manual work (ISO, 2011). This requires additional efforts both from the employees who regularly work with these processes and from corporate management. Corporate management can make corresponding resources available such as investments or the amount of work time that are required for the improvements. If the data collection for MFCA is put on the back burner from either side, this can undermine the method's effectiveness.

The norm instances a case example of an MFCA implementation in which posting processes and data quality in the merchandise management system were improved at the beginning of the MFCA implementation. For example, employees from different departments could thereby easily access the data (ISO, 2011). In combination with trainings and new report forms, this led to a large number of positive effects, so that top management expressed interest in the form of regular reports that should include the monitoring of material loss data (ISO, 2011). In this regard, Kokubu and Kitada (2015) point out that it is in fact necessary to include the losses detected with the MFCA method in the span of accountability of certain managers such as production managers. It is not sufficient to keep track of losses occurring in production processes without assigning accountability for the losses to persons who are able to reduce them. Therefore, in order to implement the MFCA method in the long run, the collection of material loss data should be combined with the accountability of the persons who are responsible for the processes behind the data (Kokubu & Kitada, 2015).

In summary, the recognition of the absence of data can be a first learning outcome in an MFCA analysis. While MFCA 1.0 evaluates material losses, thereby increasing transparency, MFCA 2.0 goes further by aiming to turn avoidable losses into products. Instead of manual one-off data collection, appropriate measures are new ways of data collection, such as digital and automated data collection methods and MFCA-specific trainings on the topic of data. The standard ISO 14051 provides practical recommendations on how to collect and handle data (ISO, 2011). With regard to the permanent use of MFCA 2.0, it is important to invest a sufficient amount of time and effort in data collection methods, processes and systems so that the calculations, analyses and conclusions building on it generate valid and useful results. Moreover, the managers who are responsible for the processes in which the losses occur should also be held accountable for the reduction thereof. This, in turn, provides the basis for effective management decisions and actions, which then increase the company's resource efficiency performance.

5.7 The MFCA 2.0 Model: Reality Construction

An MFCA 2.0 model is able to evaluate improvement measures which stem from the preceding search for material-loss-reducing measures (cf. Section 5.4) through the computation of scenarios. A scenario can include one or multiple of these improvement measures. Thereby, the MFCA 2.0 model constructs a reality based on these improvement measures and their saving potentials. Consequently, the MFCA 2.0 model constructs possible realities that provide arguments and hence support decision-making. This function of the MFCA 2.0 model will be explained and discussed in the following subsections.

5.7.1 Reality Construction Through Software Development and Application

The development of software and software models can be viewed as a process that constructs a specific reality by choosing certain options and making certain decisions. Floyd (1992) describes this as a space in which many options can be designed and tested. An important success factor with regard to software development and use is the collaboration between the individuals involved since they contribute different perspectives, thereby enriching the result (Floyd, 1992). This alternative approach to software shall be the focus of this subsection.

The result of a computer model is *autooperational form* that is expressed in *computer artifacts* (Floyd & Klischewski, 1998). Computer artifacts are able to interact with their context (Floyd & Klischewski, 1998). *Autooperational* is a neologism that was first used by Reisin (1992) to express that software is able to operate autonomously, and Floyd uses this neologism. She explains that just like a car is called *automobile* because it is able to move autonomously, a computer is a technical object that is able to move on its own (Floyd, 2002). This movement requires human action to get started and once it has been started, it is driven by algorithms and electricity, which together generate *operational form* (Floyd, 2002). The term *autooperational form* describes the structured connection and combination of single operations that together form a greater whole, i.e., an artifact which can be used by human users and which is able to influence the real world (Floyd, 2002). Floyd and Klischewski (1998) point out that the noun *informatics* also contains the term *form*, and they thereby explain how important the form is in which a piece of information is expressed. Moreover, form is related to logic, and logic, in turn, builds on the laws of language and reasoning (Floyd & Klischewski, 1998).

Based on information from the real world, computer algorithms are developed. Information can be understood as a piece of knowledge of various forms that supports, improves or enables an activity or a decision (Langefors, 1973). Through the use of the algorithms, the digital world of the model is usually completely defined, and a new version of the object or environment that was modeled gets created (Langefors, 1973). These algorithms are defined as generic as possible so that they are applicable to as many application scenarios as possible (Floyd & Klischewski, 1998). Therefore, they are detached from the specific context in which they were first detected and defined (Floyd & Klischewski, 1998). This is necessary in order to deduce the algorithm, and at the same time, certain situational information is omitted (Floyd & Klischewski, 1998). This differentiation of information is a deductive process step that requires analytical skills since the decision has to be made what objects in the form of algorithms are needed for the construction of the model world (Floyd & Klischewski, 1998). Nevertheless, Floyd and Klischewski (1998) advise to include empirical, experimental and recursive elements in the modeling process such as prototyping and low-level communication processes that support consensus-finding. The formalization through computer algorithms reduces the degree of complexity by focusing on the aspects that are relevant for the model (Floyd, 2002). At the same time, the formalized model represents an artifact that offers a new field of action for its users since the algorithms can be applied to new specific situations, thereby recontextualizing the algorithms (Floyd, 2002). This will help the users to develop and consider different options for action based on a specific situation (Floyd, 2002).

Moreover, there are two types of modeling: discrete and continuous. Discrete modeling allows to define different states of the model which are reached through certain events (Floyd & Klischewski, 1998). Compared to continuous modeling that does not consider certain events, discrete modeling is related more closely to computer science since it considers discrete changes. Generally, it is important to understand that the calculation results of the model are not immediately applicable to a specific situation. To be used in a specific situation, the results need to be transferred and interpreted.

Since computer models are an operational reconstruction of a natural, technical, social or idealistic situation or object, the creation of such a model has a social dimension as well. It is a fallacy to assume that the quantitative formalization of the process(es) under analysis makes them thereby controllable (Floyd & Klischewski, 1998; Maaß & Oberquelle, 1992). Usually, multiple persons are involved in the creation and for this reason, it is important to communicate well regarding the framework conditions and the different influencing factors (Floyd & Klischewski, 1998). For example, different guiding principles, values and ideals play a more or less visible role (Floyd & Klischewski, 1998). Software practitioners always act in a social context, and their work can initiate change in an organization (Floyd, 2002). Furthermore, building the model challenges traditional ways of thinking and sharpens the self-perception of the persons involved in the project (Floyd & Klischewski, 1998). As a result, the artifact of a model is not only embedded in human options for action, but it is able to generate options for action at the same time (Floyd & Klischewski, 1998). Therefore, it is important to consider social situations and aspects when building and using models because this opens the process for the social dimension.

From a socio-theoretical point of view, there are two approaches to software and the results it generates. While one is based on philosophical realism and argues that software enables an objective view, the other one is based on philosophical constructivism and takes the view that software enables a subjective perspective (Floyd, 2002). Floyd (2002) notes that the development of software has an impact on the real world and that it is therefore constructive in its nature. She draws on ideas and arguments of the constructivist discourse, which, for example, S. J. Schmidt (1987) surveyed. A research project on the topic of corporate energy and material flow management used the revised version of the St. Gallen Management Model by Rüegg-Stürm (2003) and argues that it represents a constructivist approach (Schwegler et al., 2007). Reality cannot be captured as such, but instead, it can only be understood and interpreted with the help of existing knowledge (Rüegg-Stürm, 2003). This knowledge is a personal matter and therefore, reality is perceived and constructed subjectively, which Rüegg-Sturm (2001) also applies to organizations and organizational change.

Floyd and Klischewski (1998) conclude that computer models—representing computer artifacts—have two kinds of impact from a social perspective. First, a model requires a certain level of abstraction to build the model world that generates added value for its users. To achieve this level of abstraction and to understand and interpret the model and its results, the users need to mentally interact with the model and the model world (Floyd & Klischewski, 1998). These activities require time, training and practice, and they need to be approved and supported by corporate management, for example, through their inclusion in job descriptions. Second, models are autooperational, meaning that their use has an impact on the real world including its social dimension (Floyd & Klischewski, 1998). The actual influence depends on the overarching goal of and the context in which the model is used. The goal can be an increase in productivity, but the authors also put up goals for discussion like resource conservation and the idea of a sustainable economy (Floyd & Klischewski, 1998).

This understanding of computer science and computer models stands in contrast to the arithmetic worldview that suggests that numbers are objective, rational and right. Moreover, this worldview is based on the idea that numbers are sufficient to depict a specific situation or object, and it rates a scientific discipline or theory depending on how arithmetic and quantifiable it is (Floyd & Klischewski, 1998). Although the increasing digitization and use of computers foster this tendency, Floyd and Klischewski (1998) argue that they were not its cause. The authors make alternative suggestions to rethink the application field of computer science by opening its scope beyond arithmetic operations. Having clarified their position, the scholars request from the discipline of computer science to first of all recognize that there are realities which cannot be formalized in algorithms. Second, they propose to contextualize the discipline so that the aspects that cannot be formalized are included in computer science as well (Floyd & Klischewski, 1998). Third, they discuss the responsibility that comes along with computers artifacts. Their powerful autooperational form can be misleading because its use has an impact on the real world, although is not able to carry responsibility for its action (Floyd & Klischewski, 1998). The scholars evaluated this disparity problematic from a societal point of view already in 1998.

In summary, computer science creates autooperational agents that can explore new options for action with regard to a specific objective or issue that connects formal, social and technical aspects (Floyd, 2002). Computer software is able to perform calculations in place of and for a human being, but it cannot execute actions the way human beings can (Floyd, 1992). Therefore, activities of computer artifacts need to be guided, accompanied and reviewed by a human authority who also carries responsibility for them (Floyd & Klischewski, 1998). This is a non-negotiable requirement for the creation and use of computer artifacts such as computer models. It relates to the responsibility associated with managers and for which they should be held accountable, which has been pointed out in Section 5.6. In this way, computer science can operationalize certain questions and make a positive impact on the real world.

5.7.2 Reality Construction With MFCA 2.0 in a Corporate Context

Rethinking these thoughts in light of MFCA 2.0 offers new ideas on how to apply the software and on how to use the models created with it. First, an MFCA 2.0 model is a computer artifact of operational form that is based on certain relations expressed in algorithms. It does not contain all aspects existing in the real world because it focuses on a specific question or problem. Although the question whether something should be included in the model or not is a balancing act, the critique of it would be a straw man fallacy since the goal of a model is not to map the real world as accurately as possible. Instead, the focus on a specific question or problem reduces the degree of complexity, enables new perspectives and thus creates new opportunities. MFCA 2.0 does not dissolve the philosophical tension whether a software is realist-objective or constructivist-subjective, but it rather links the two views. An MFCA 2.0 software model is realist-objective in the sense that it first focuses on real material losses and their quantification. Second, it is constructivist-subjective because it enables the definition of scenarios by the software users based on loss reductions and hence quantifies potential savings. In this way, the model creates an artifact-based field of action containing different scenarios and conditions that allow the exploration and evaluation of saving potentials. The implementation of a loss-reducing measure represents a discrete modeling approach since the impact of this alteration on the model gets determined.

Second, the MFCA 2.0 model should be viewed in its context including the social aspects and not be viewed in an isolated way. Both its creation and its use challenge the people involved and encourage them to think outside the box. Through recontextualization, the model provides food for thought for its users and enables new perspectives on existing questions or problems. This may seem surprising since the model is apparently quantitative at its heart. However, the numbers are the result of a multitude of decisions and aspects that are not explicitly specified in the model. Nevertheless, it is important to be aware of these non-numeric facts to correctly use the model and to increase its benefit. This includes, for example, strategic aspects, the corporate management structure and policy and the company's attitude regarding GHG emissions. Therefore, the interpretation of the MFCA 2.0 results requires knowledge about the measure(s) included in the scenarios in order to comprehend the saving potentials. Depending on the preferred criterion (physical, economic or ecological), certain figures in the model results can be used for a decision such as GHG emissions or costs. These contribute to overarching goals such as an increase in productivity or a reduction of resource use in production.

Third, the use of an MFCA 2.0 model requires time, training and practice. These three, in turn, require employee capacity and management support. These framework conditions are prerequisites to first of all build an MFCA 2.0 model, but also to use and analyze the model correctly. These upstream and downstream requirements are very important for the successful use of the method.

Fourth, the implementation of a measure that was explored with the MFCA 2.0 model is going to remain a task for human beings in the future. Just like responsibility cannot be carried by a computer, a computer is not able to realize the saving potential associated with an improvement measure. This important step remains outside of the model and is subject to human decisions and activities.

Schwegler et al. (2007) support these four statements with their applied research on corporate management of energy and material flows. Corporate material and energy flow models are a means to improve the understanding of connections and backgrounds (Schwegler et al., 2007). This kind of model does not depict reality in detail because the model acknowledges that reality is more complex and that there are factors the model does not contain or foresee (Schwegler et al., 2007). The straw man fallacy describes this inaccuracy. Therefore, the authors differentiate this functional aspect from so-called decision models, which generate definite statements and are therefore used for projections in the basic sciences (Schwegler et al., 2007). Furthermore, Rüegg-Stürm (2003) sees the following objectives of models: the quick identification of the aspects that are relevant, the identification of interdependencies between different parameters, the support of corporate communication and hence the company's capability to act through the focus on the model. In summary, the model creates a new language-based version of reality. This new reality is helpful for problem solving since the model represents a facilitator for communication and sensemaking (Rüegg-Stürm, 2003).

The MFCA 2.0 model is an explanatory model that is able to quantify and analyze relevant material and energy flow models including scenarios thereof. It constructs a reality that invites and challenges the persons involved to discuss and make decisions. In this way, the model provides practical support in a complex corporate reality.

5.8 Insights From the Practical Application of MFCA 2.0: Two Case Studies

This dissertation is related to the research project MaFImA (Hedemann et al., 2023), a joint project by iPoint-systems GmbH and Pforzheim University. The project was funded by the Baden-Württemberg Ministry for the Environment, Climate and Energy Sector. Within the scope of MaFImA, two case studies were developed that accompanied the research activities of this dissertation. Since the case studies were completed after the termination of the MaFImA Project, they were included in this research work. In both case studies, the new approach of MFCA 2.0 was applied to specific examples from corporate practice. This will be described in the following two subsections. Due to non-disclosure agreements with the companies, the information was in part anonymized, generalized and shortened.

5.8.1 Case Study 1: Material Losses in a Milling Process

This case study was conducted in a family-owned company that belongs to the mechanical engineering sector. The company has 250 employees (June 2023) and it hence counts as a large enterprise (OECD, 2024). In June 2023, the company was preparing the introduction of an environmental management system with the goal to thereby fulfill the requirements of the standard ISO 14001 (ISO, 2015).

The product that was selected for an analysis with MFCA 2.0 generates about 60% of sales revenue and is therefore of high relevance. Its ecological footprint is likely to be of high relevance for the company from an environmental management perspective as well. Alternative selection criteria would be products whose production processes generate a lot of waste or whose production cost is high compared to other products. In this case study, the choice was made in close coordination with the company. This is very important in order to meet the company's expectations and to maintain the motivation of the employees who are involved.

The method MFCA 2.0 was applied to compare the GHG emissions of two product alternatives with the same product function. The two alternatives differ in the main component of the selected product and in further components. Notwithstanding the differences regarding the materials, the two alternatives offer the same product function. The main component is produced in-house (status quo scenario) and the alternative is obtained from a supplier (improved scenario). The in-house production method uses steel as material and includes a milling process that generates a significant amount of material loss in the form of steel chips. The alternative production method uses aluminum for one component, and it is produced with an extrusion press. The extrusion press does not entail any metal chips nor other forms of material loss since the metal gets pressed into the product shape. However, this manufacturing process is undertaken by a supplier who then provides the semi-finished product. This limits the data availability of the upstream process, but it does not impede the comparative analysis.

An important aspect suggests that the measure leads to a decrease of the GHG-based environmental footprint of the product: The steel-processing production method generates material loss in the form of metal chips, which is why much more material is needed to in the production process. Nevertheless, the alternative comprising the aluminum component requires additional components made from steel. Therefore, the question whether this alternative causes less GHG emissions remains to be examined. A guided tour through the selected product's production process with watchful eyes revealed the following material losses:

- Milling process: 50% of steel input steel turns into steel chips
- Cutting process: 14% of steel input is cut, of which 11 percentage points are reused and the remaining 3 percentage points are accounted for as scrap metal
- Cooling lubricants

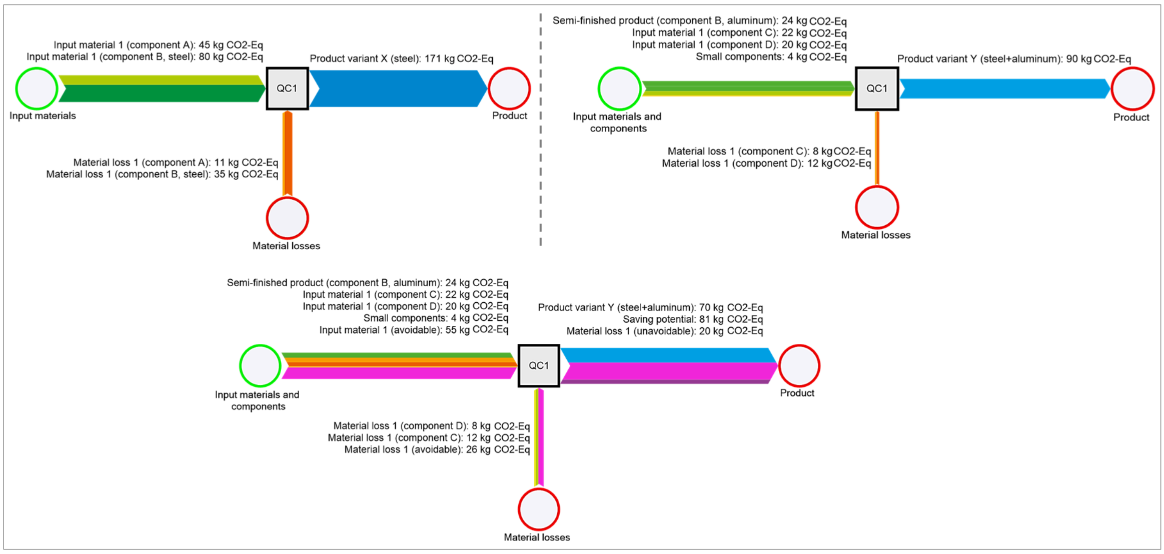
After the guided tour, the decision was jointly taken to limit the data collection to the components that are different between the two options. This decision is a decisive element of the project because it was not the goal to determine the absolute amount of GHG emissions of the two products. Instead, the goal was to calculate the difference between the two options, thereby making a comparative analysis between the status quo and the improved scenarios. Based on the MFCA 2.0 approach, the difference between the two scenarios reveals the saving potential of the improvement measure.

The following data collection was composed of different sources. First, data was directly measured in the company. Second, data was requested from two of the company's suppliers. Third, data was used from the Ecoinvent database (Ecoinvent, 2022) and fourth, data was derived from a sector-specific study that was kindly made available to the project leaders through a company representative. Moreover, the electricity demand of the milling process was documented for a certain amount of metal chips. Because this was not the product-specific amount of metal chips, the data was extrapolated to one product.

Figure 60 contains three different Sankey diagrams for the GHG emissions measured in CO_2 equivalents. The diagram at the top left shows the current scenario including the in-house production of the components under analysis. The product (product variant X) consists of the two components A and B, whose production leads to material losses, respectively. The improved scenario is depicted in the diagram at the top right. The product (product variant Y) requires four components, of which one is procured as semi-finished product. This component is made from aluminum and produced in an extrusion press, avoiding the material loss of 35 kg in the form of metal chips. However, the additional components C and D are required which both entail material losses.

The Sankey diagram at the bottom of Figure 60 represents the MFCA 2.0 approach by combining the upper two diagrams. The pink shares of the arrows indicate the saving potential related to the change from product variant X to product variant Y. This change leads to the reduction of 81 kg CO_2e or 47%, representing the measure's GHG emissions-based saving potential. This saving potential is composed of 26 kg CO_2e related to the reduction of material losses and of 55 kg CO_2e related to the different material composition of the product. The emissions related to the material losses can be reduced from 46 kg CO_2e to 20 kg CO_2e, which is a reduction by 57%. Furthermore, the physical mass of product variant Y is 29 kg lighter than product variant X, which could be of relevance, e.g., with regard to transport and its use phase. These figures provide valuable decision support with regard to the alignment of a company's sustainability strategy. The MFCA 2.0 results can pave the way for reductions of the company's GHG emissions and make its products more resource-efficient.

Figure 60: Sankey diagrams Case Study 1: Product variant X (top left), product variant Y (top right) and MFCA 2.0 (bottom)—GHG emissions-based flows



Case Study 1 enabled the following four learnings:

- It is advisable to first get an overview of the production facility, the relevant processes and the first sighting of accruing material losses, for example, in waste collection containers. This first step will help to prepare the definition of the scope for the MFCA 2.0 analysis. In this case study, the measure represents a product alternative, and the measure should be evaluated regarding its GHG emissions saving potential. Therefore, the data collection effort could be significantly reduced.
- Even if the data was collected directly from the running production process, the data cannot always be immediately transferred to the model. Sometimes, it needs to be extrapolated or adapted to match the scope of the model.
- When searching for improvement measures, it can be helpful to look beyond the factory gates and to think about how changes in the upstream and downstream processes could improve the supply chain. An example is the supply of semi-finished products or measures that are implemented in the client's production process. It should be noted that in a specific application, this may raise new questions because up- and downstream processes are not easily available for data collection. It may take more time for data collection or require the formulation of assumptions.
- Finally, an improvement measure does not merely lead to a reduction of material demand, but it can also lead to a change of the material composition. This will affect the material losses as well. For example, new production processes may require different materials, thus generating an alternative product variant. The alternative product variant can then be compared and analyzed—depending on the focus of the MFCA 2.0 analysis—regarding physical, economic and environmental indicators.

5.8.2 *Case Study 2: Material Losses in a Laser Cutting Process*

Case Study 2 is a second practical example that was carried out in a company belonging to the mechanical engineering industry. The family-run company develops and produces special machinery, and it has about 300 employees (December 2023), qualifying it as a large enterprise following the classification of the OECD (2024).

For the case study applying MFCA 2.0, one of the company's mass products was chosen, whose production volume exceeded 8,000 units in 2022. The project was started with a guided factory tour. The tour focused on the production processes of the selected product, and it disclosed the following five items of waste:

- 15% sheet metal cutting loss in the laser cutting process
- Waste water
- Paint and coating waste
- Different recyclable waste materials (in German: "Altstoffgemisch")
- Waste oils

The data collection and data review resulted in a large amount of data, offering a basis for the application of the MFCA 2.0 method. During the analysis, it turned out that the allocation to the different products and therefore the quantification to the selected mass product is difficult. For example, the company's energy demand could be quantified for the different types of energy electricity, heating oil and natural gas. However, an allocation key distributing the demand to the different machines and products could not be defined within the time frame of the project. Appropriate measuring instruments were expedient in this situation to collect precise data for the application of MFCA 2.0. This requires preparation time and personnel capacity, and it should therefore be planned and communicated accordingly in a timely manner.

The following four ideas for improvement measures or starting points were collected. They are to be further evaluated regarding their effect on costs and environmental emissions, respectively.

- Measures can reduce the amount of metal cutting waste, possibly in cooperation with the suppliers of the laser cutting machines and the metal sheets. This would lead to a reduction of the material demand in the laser cutting process.
- The different recyclable waste materials should be analyzed in detail. It is worth investigating whether their separation in different waste groups increases their recyclability—leading to a reduction of GHG emissions in the recycling process—and whether it offers financial advantages. This does not automatically reduce the amount of waste, but it can still lead to environmental and economic improvements.
- It turned out that the disposal company collecting the company's waste paper offers a cost reduction if the amount of waste paper exceeds a certain amount. Although this measure does not reduce the amount of paper waste, it would generate a financial benefit and make the collection process more efficient. One condition of this measure is that the company is able to store the paper waste until it gets collected. It should be verified and ensured that the company can fulfil this condition before the measure gets implemented.
- The self-sufficient electricity supply through renewable energy production and storage is a measure that could significantly reduce the energy-related costs and GHG emissions compared to the status quo.

In the next step, the impact of the first bullet point (reduction of metal cutting waste) was elaborated and illustrated. To do so, the scenario-based algorithm of MFCA 2.0 was applied. A potential improvement measure could be rooted in the optimization of the physical dimensions of the metal sheet or the cutting approach. The following Figure 61 illustrates a Sankey diagram focusing on the laser process in QC1. The diagram refers to the production of one product unit, and it combines the status quo and the scenario including an improvement measure. The potential improvement measure affects the laser process in QC1, assuming that the metal sheet cutting loss of 80 kg can be completely avoided. As can be read off from the two input flows in QC1 (laser process), the total saving potential per product unit amounts to 80 kg input materials and 144 MJ electricity. Moreover, the monetary and GHG-based saving potentials amount to 226.40 EUR (cf. Figure 62) and 362 kg CO_2e (cf. Figure 63), respectively. These two values can be read off from the product flow in Figure 62 and Figure 63, respectively, since the costs and GHG emissions are accumulated along the production process. Following the algorithm of MFCA 2.0 (cf. Section 4.3), these figures represent the maximum saving potentials. Depending on the specific improvement measure and the consequent reduction of the material loss flow, the actual savings can be lower. Based on specific measures, the resulting saving potentials can be calculated with the scenario-based approach.

Figure 61: Sankey diagram Case Study 2, cutting loss is avoided—physical flows

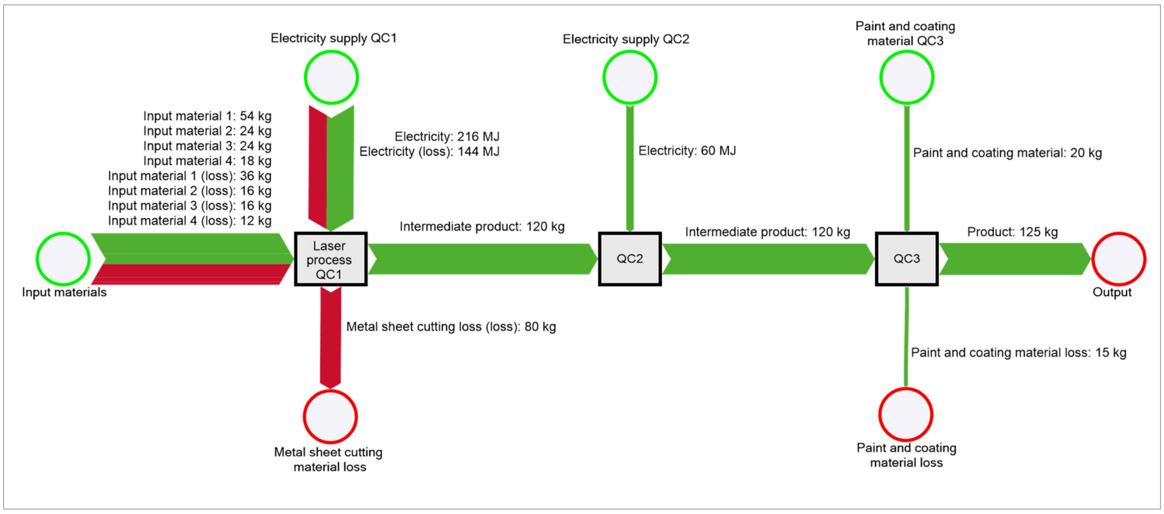


Figure 62: Sankey diagram Case Study 2, cutting loss is avoided—monetary flows

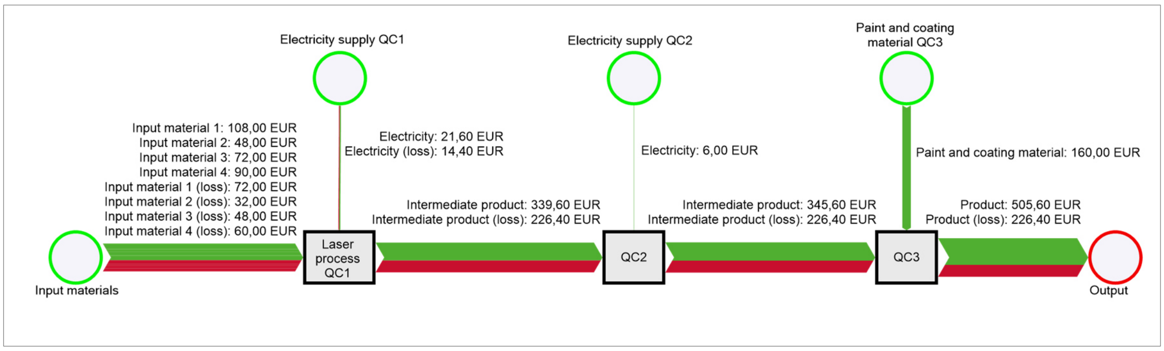
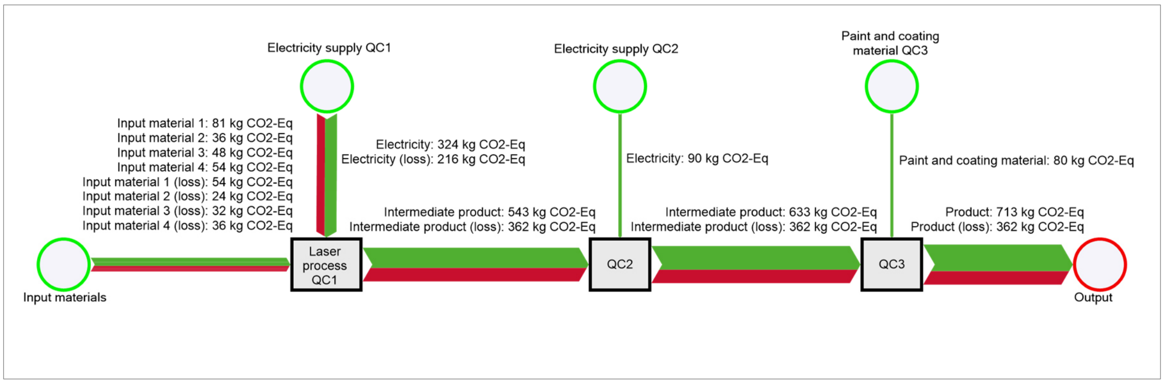


Figure 63: Sankey diagram Case Study 2, cutting loss is avoided—GHG emissions-based flows



Case Study 2 led to the following two main insights:

- The configuration of the laser process (QC1) was carried out by the supplier of the laser machine, whereas the company that owns the process and the machine equipment has very limited impact on the machine setup and settings. Therefore, the assessment and implementation of improvement measures require close cooperation with the supplier. Moreover, the supplier can possibly offer further ideas and support regarding improvement measures and loss reductions upon request.
- The analysis of the production data has shown that the two production cost components machine-hour rates and person-hour rates have changed significantly for several production steps over the last years. The two largest increases were registered for the painting and manual metalwork. The largest decreases were registered for the three processes welding, manual postproduction and manual finishing. During the project, no apparent reason could be identified for the large changes or deviations. These developments can significantly influence the monetary assessment of the material losses, the corresponding saving potentials and the prioritization of improvement measures. In order to understand the reasons for the changes, further analyses are required. The results can then be discussed with the people that are responsible for these production steps and with the production workers. This approach will ensure that the data is valid and understood correctly, thus generating additional value for the company as a result of the MFCA 2.0 project.

6 Discussion

A lively discussion is usually helpful, because the hottest fire makes the hardest steel.—Tom Clancy

The aim of this chapter is to reflect this research work. This includes the discussion of the research results against the background of their theoretical basis and the relevant literature. Challenges, limitations and further research areas will also be addressed in a critical reflection. Finally, the topic is viewed in the context of the sustainability challenge and the greater object of sustainable development.

6.1 Discussion of 20th Century Cost Accounting, MFCA 2.0, and the Consulting Concept

The development of cost accounting in the 20th century provides a good basis for the methodological advancement of the MFCA method (Research Question 1). The development led from absorption costing to marginal costing, gradually changing the discipline over time. Research Questions 1.1 and 1.2 particularly address the methodological debate between Kilger and Riebel (cf. Sections 2.4 and 2.5) and the analysis of the debate offered valuable insights. Both scholars excluded certain cost categories and developed a decision-oriented cost accounting approach, thus making the discipline future-oriented by changing the discipline's viewing direction. Moreover, the continuous debate between Kilger and Riebel did not only fuel the discipline's further development, but the two scholars—especially Kilger and Plaut—also disseminated their approaches with supporting activities such as conferences and trainings in order to promote the application in practice (Kilger, 1993). The combination of theory and practice was a decisive element in the advancement and refinement of their work. Despite the differences of opinion, they shared a motivation: They agreed that absorption costing was not the right way to provide decision-oriented support of corporate cost accounting.

It was Plaut who had first developed flexible standard costing and turned it into a business case (Kilger, 1993). He founded a consulting company that implemented the marginal approach in corporate practice, and he then refined the cost accounting approach over time (Kilger, 1993). Accompanying Plaut's work, Kilger developed the approach for academia and embedded it scientifically. For this reason, it is called *Kilger's Flexible Standard Costing and Contribution Margin Accounting*. Differential costs are the decisive aspect, and they are based on Schmalenbach's ideas that he had published many years before already (cf. Subsection 2.4.2). The calculation of contribution margins is useful for decisions that concern a possible extension of the production range and for decisions that need to be made when production capacities are reached (Kilger, 1993). This can optimize a company's profitability and accelerates the coverage of fixed costs (Kilger, 1993). Kilger's work was reissued multiple times, and he also provided changes over time, such as the development of dynamic marginal costing. This approach did not become popular in corporate practice—mostly because it has a focus on the costs' due date structure. In summary, *Kilger's Flexible Standard Costing and Contribution* has become an important pillar of modern cost accounting, and it is indispensable when reviewing the history of cost accounting.

Riebel developed his approach called *Generic Direct Costing and Contribution Margin Accounting* in a similar time frame as Kilger and Plaut. Being a chemist, Riebel chose a meticulous and academic way. He completely rejected the linearization and allocation of costs, and he therefore avoided these in his approach (Riebel, 1994b). Instead, he introduced the identity principle, which focuses on corporate decisions as the main criterion. Moreover, cost considerations require a reference object that also helps to identify which costs are relevant for a particular cost consideration (Riebel, 1994b). In this way, the reference objects can be ordered hierarchically. This enables the gradual inclusion of overhead costs, finally leading to the inclusion of all cost components (Riebel, 1994b). Riebel's cost accounting system comprises a purpose-neutral accounting database, which provides the basis for cost analyses for different specific purposes (Riebel, 1994a). This idea will be taken up again in Section 6.2 with the suggestion of a corporate master data repository.

The two approaches differ largely regarding the handling and integration of costs. They follow different paths to decide whether certain cost components are relevant for a specific application (Research Question 1.2). While Kilger's and Plaut's key aspect is proportionality, Riebel's key aspect are decisions. Kilger authored a comprehensive and structured monograph that was reissued 12 times already. Riebel, on the other hand, authored single articles that were then published as a compilation of these articles. This difference may have influenced the approaches' comprehensibility and dissemination, respectively (Franz, 2017a). Although the scholars chose different pathways, they shared the same motivation: They were both open to changes and adjustments of their approaches in order to develop a more accurate cost accounting approach.

Moreover, *Riebel's Generic Direct Costing and Contribution Margin Accounting* was analyzed in light of the advancement of the MFCA method in this research work (Research Question 1.3). Riebel (1994b) argued that costs can only be rightfully allocated to a cost object if they are both caused by the same decision. This was formalized in the identity principle that strongly focuses on decisions. Furthermore, Riebel argues that a decision should only imply costs that accrue because of that decision (cf. Paragraph 2.5.4.2). This represents a valuable idea which can be transferred to MFCA and the evaluation of improvement measures. MFCA 2.0 strives to quantify the costs that can be saved in consequence of the implementation of one measure or a combination of multiple measures. These insights provide the basis on which the following research questions can be answered.

The decision to implement an improvement measure in a system under analysis—leading to the improved scenario—is what enables physical saving potentials at first. MFCA 2.0 compares the status quo scenario with the improved scenario that includes the improvement measure, and the difference yields the saving potential. The scenario-based approach allows the quantification of the saving potential based on specific improvement measures that reduce material losses (Research Question 2). This characterizes MFCA 2.0 at its heart (Research Question 2, cf. Sections 4.1 and 4.2). The algorithm of MFCA 2.0 is versatile and it can be applied to many different use cases. These include reductions of material loss flows below 100%, which is a common case in production processes due to technical conditions (Research Question 2.1, cf. Subsection 4.3.4). The algorithm can also handle simultaneous reductions of multiple loss flows (Research Question 2.2, cf. Subsection 4.3.4). Moreover, it can be applied to material loops. Depending on what the status quo scenario and the improved scenario are, the algorithm is able to evaluate the system under analysis either with or without a material loop (Research Question 2.3, cf. Subsection 4.3.5).

The scenarios are based on physical material and energy flows. With the help of cost factors and GHG emission factors, they can be transferred to the economic and environmental dimension, thus leading to monetary and environmental saving potentials. This methodological approach to GHG emissions teaches its users that the calculation of GHG emissions and the corresponding saving potentials follows the same logic and algorithm as the calculations with costs (cf. Subsection 4.3.4). The results of these calculations provide meaningful information for a company, and they offer practical support for management decisions. Depending on the company's goals, different indicators as a result of the MFCA 2.0 analysis can be preferred. For example, a measure could increase the overall energy demand, while it reduces material losses. These changes should be weighed against each other and additionally, the monetary and environmental effects can be examined. In this way, corporate management can make appropriate, context-specific decisions.

In summary, like cost accounting was refined and adapted to business practice, MFCA has been developed over the years, growing an extensive body of case studies and other application examples. With MFCA 2.0, the method has been developed further and now considers the needs of corporate practice. It can evaluate and compare the effects of different options for action in the form of improvement measures in physical, GHG emissions-based and monetary units. With regard to today's pressing environmental and economic challenges, MFCA 2.0 is a highly practical tool that helps to find specific answers to pertinent questions.

This change at the heart of the method leads to several follow-up questions that were answered with a consulting concept (Research Question 2.4). The questions cover a wide range from the purpose of consulting, the search for improvement measures to the implementation and permanent integration of MFCA 2.0 in corporate practice. Moreover, a differentiated understanding of the MFCA data and a new understanding of the MFCA model based on MFCA 2.0 were developed and included. The consulting concept related to MFCA 2.0 and its exemplary software implementation (cf. Section 4.3) also incorporates the potential critique that the method takes a purely technical perspective on the losses. A company incorporates much more than its production processes, which are depicted with the material and energy flows in the MFCA model.

Just like the critique regarding the practicability of Kilger's cost accounting approach was silenced with the fast development of data processing, the software application of MFCA 2.0 based on the new algorithm is not mandatory. However, it can certainly support the acceptance of the method in a corporate environment. Three criteria for effective implementation of such software are an appealing user interface, easy handling and the compatibility of the software with existing software applications. Additionally, a web application service could be considered since it offers quick and easy access that reduces installation work.

Computing systems such as software models may entice their creators and users to think that they give them control of the process(es) they depict (Maaß & Oberquelle, 1992). This general point of criticism that an MFCA software is too mechanistic can be replied with Floyd's (2002) claim that the use of software should take place in the context of human cooperative behavior and action. If their use lacks the different perspectives of the people involved, unforeseen and useful new ideas can become missed opportunities (Floyd, 1992). Therefore, MFCA 2.0 actively invites new ideas and embraces the social dimension to develop novel measures that reduce material losses.

Consequently, the method does not merely create and increase transparency about material losses as it is described in the standard ISO 14051 (ISO, 2011). The norm was taken as basis for many research projects and papers. Some of them applied the method and authored case studies (e.g., Bux & Amicarelli, 2022; Fakoya & van der Poll, 2013; Kasemset et al., 2015), while others combined the method with additional approaches such as management perspectives or lean management (e.g., Chattinnawat et al., 2018; Chompu-inwai et al., 2015; Kokubu & Kitada, 2015; Kokubu et al., 2023). MFCA 2.0 does indeed create and increase transparency in a first step, but it goes further and strives to reduce the losses with improvement measures, which are then evaluated with the scenario-based approach. Thereby, MFCA 2.0 fulfills the act step of the PDCA cycle and closes the continuous improvement cycle as described in the standard ISO 14051 (ISO, 2011, p. 29). Section 3.6 concluded that a full implementation of the PDCA cycle within the method needs to ensure that an actual loss reduction takes place, for example, through the implementation of an improvement measure. This methodological advancement of MFCA significantly increases its practical focus and thus makes it more relevant and attractive for the manufacturing industry.

The scenario-based approach in combination with the consulting concept represents a paradigm shift for the MFCA method. This has been suggested and described particularly for material loops by Viere et al. (2010) and M. Schmidt (2012). MFCA 2.0 provides a new kind of decision support for short-term and long-term corporate decisions based on production processes and the corresponding data. By combining physical information, cost data and an environmental view based on GHG emissions, it offers an integrated approach uniting resource use, cost analysis and the carbon footprint. MFCA 2.0 can now complement other cost accounting systems by pointing out the saving potentials of material-loss reducing improvement measures. Just like Kaplan (1988) argued in his article titled "One Cost System Isn't Enough", Günther, Rieckhof, et al. (2017) argued with regard to MFCA that it will not replace but complement regular cost accounting. Consequently, MFCA 2.0 does not replace nor compete with regular cost accounting, which is usually practiced in a company. Instead, it complements corporate management by offering a perspective that quantifies the physical, monetary and environmental saving potentials of different improvement measures.

The scenario-based approach proves useful for many different purposes since an improvement measure can have different forms. For example, it can include upstream chains, i.e., supply chains, which require a close cooperation with suppliers to implement the measure. Once the relevant suppliers have made their data available, the impact of potential improvement measures, i.e., their saving potentials and respective risks, can be evaluated and discussed. This information can also be useful for strategic decisions such as pricing and market positioning. Further questions relate to corporate decarbonization plans or end-of-life options such as remanufacturing or recycling. Moreover, an improvement measure can be evaluated from a tax-related perspective. For example, the tax-related effects of decisions to outsource or include certain production steps can be quantified with the scenario-based approach as well.

These application examples show how MFCA 2.0 with its scenario-based approach can broaden the corporate viewpoint not only with regard to the physical, monetary and environmental dimension, but also with regard to a multitude of other questions. MFCA 2.0 also addresses the critique that Kokubu and Kitada (2015) formulated regarding the prioritization of improvement proposals based on MFCA. The authors argue that management will prioritize other future profits and growth opportunities, which is not the focus of MFCA 1.0 (Kokubu & Kitada, 2015). Due to the focus on saving potential and the resource-based, economic and environmental perspective, MFCA 2.0 is more decision-oriented and hence of higher relevance for management. Together with the consulting concept, the method offers a holistic approach including decision support for corporate management.

Like the implementation of a cost accounting system both requires management support (Krumwiede & Suessmair, 2008) and provides management support (Riebel, 1994b), the successful implementation and use of MFCA 2.0 as a management tool also depends on the support from managers (Christ & Burritt, 2016; ISO, 2011). Moreover, MFCA 2.0 and the consulting concept depend on employee support, for example, for the successful cooperation with an external consultant following a process consulting approach (cf. Section 5.3; Ellebracht et al., 2018; Ennsfellner et al., 2014) and the successful search for measures (cf. Section 5.4; Patzak, 1982). Employee support is an essential element of MFCA 2.0—as it is for lean management (Bertagnolli, 2018)—and it is difficult in practice to generate this element in case there are reservations or doubts regarding the method. The development, identification and implementation of adequate improvement measures require both employee and management support.

When using MFCA 2.0 and applying the corresponding consulting concept, it is important to beware that it is not a straight line because it requires communication, coordination and interaction between the different persons and departments involved. The element of reciprocity can also be found in Riebel's and Kilger's cost accounting approaches. Riebel (1994b) emphasizes that his cost system is the result of theoretical ideas and practical testing, thus making it a decision-focused management tool. It does not need to be implemented at once, but it can be implemented stepwise or in parts only (Riebel, 1994b). Kilger (1993) argues that his costing approach is the result of the level of development of cost accounting on the one hand and the level of development of software products at the time he published his ideas on the other hand because they are both decisive for corporate cost accounting practice. Moreover, systems engineering combines analysis and synthesis in a reciprocal manner to develop improvement measures (cf. Section 5.4, Patzak, 1982). This new understanding of a computer model in the context of human activity describes the interaction of the two (cf. Section 5.7, Floyd, 2002). The interaction allows less preliminary planning, but the new elements paint a more realistic picture and are more action-oriented by quantifying saving potentials of improvement measures, thereby increasing the method's effectiveness. MFCA 2.0 does not need to be implemented to a company at once, but to begin with, it can focus on a certain product or a process, thereby reducing the effort of data collection and processing.

This work has shown that although MFCA has not spread in practice yet, the methodological advancement of MFCA 2.0 enables new potential for its application in practice. The improved method enables an increase in resource efficiency in manufacturing processes and chains, and this has multiple positive consequences for the company's performance. Especially the combination of the physical, economic and ecological dimension in the MFCA 2.0 algorithms are a promising aspect because the concept of sustainability is multi-dimensional as well. Sustainable development requires the inclusion and pursuit of different goals such as resource-efficiency, but also an absolute reduction of global resource use. Furthermore, economic stability and a reduction of environmental impacts such as GHG emissions to combat global warming are important elements of sustainable development. There is no universal formula for sustainability, but it has the characteristic of a mosaic picture (cf. Section 1.2) and it requires constant alignment with the broader picture.

The authoring of this dissertation in the English language makes this methodological improvement accessible and comprehensible to the international community of academia and industrial companies. German cost accounting has been a research subject of interest for international scholars for a number of years (e.g., Friedl et al., 2009; Keys & van der Merwe, 1999; Krumwiede, 2005; Krumwiede & Suessmair, 2008; Sharman & Vikas, 2004). Considering the urgent need for action regarding the global sustainability challenge, it appears useful to address a large global target group to increase the impact of the research results.

The manifold meaning of MFCA 2.0 can also be viewed from the broader perspective of resource use and its economic and environmental consequences (e.g., measured in EUR and kg CO_2 equivalents). As Section 1.4 pointed out, the meaning of global resource demand and material extraction figures have significantly increased over the last decades (IRP, 2019; based on UNEP & IRP, 2018). The IRP (2019) addresses the relationship between material efficiency, waste management and GHG emissions. The EU's and also Germany's high dependence on raw material imports increases the relevance and need of resource efficiency (cf. Sections 1.3 and 1.4). For example, the value of the EU's raw material imports in 2022 has increased to more than 125 B EUR (cf. Section 1.4, Figure 2; Eurostat, 2024). In the period between 2013 and 2023, the trade balance for raw materials reached the maximum of –49.1 B EUR in 2022, pointing out the urgency of this unbalanced relationship. Germany's trade balance for energy and metal amounted to –191.1 M t (raw materials for energy) and –37.1 M t (raw materials for metals) in 2022, respectively (cf. Section 1.4, Table 1; BGR, 2024, p. 22). Although both values have decreased for the following year 2023 (cf. Section 1.4, Table 1; BGR, 2024, p. 22), the import values by far exceed the export values, mirroring Germany's high import dependence in physical and monetary terms (cf. Section 1.4, Table 1 and Table 2; BGR, 2024, pp. 21–22).

Undoubtedly, international trade is an important and useful aspect of today's world economy. However, considering the identified high raw material dependence, von Carlowitz' (1713/2022) statement that a country that does not depend on imports should be considered fortunate, appears in a different light. Sustainable development implies the efficient use and conservation of resources, and the raw material dependence underlines this imperative. To reduce this resource dependence and hence the economy's supply vulnerability, the evaluation of material-loss reducing improvement measures is—among other activities—a promising path. A country that reduces its raw material dependence by using raw materials sparingly and efficiently is competitive, future-proof and therefore sustainable. Such a country and its manufacturing industry take the definition of sustainable development in the Brundtland Report—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987, chapter I, para. 27)—serious and they respect the limits of our planet.

Since the reduction of environmental impacts such as GHG emissions has developed from an optional endeavor to a competitive advantage over the last years, the environmental evaluation of improvement measures in kg CO_2 equivalents is a very relevant feature of MFCA 2.0—besides the evaluation in physical and monetary units. To reduce their environmental impact, the compensation of GHG emissions is common business practice. Due to a lack of know-how, the shortage of specialists in this field and the risks associated with production modifications, the actual reduction of GHG emissions poses an obstacle to many manufacturing companies. Compensation with financial means seems to be the better option. However, according to the standard ISO 14068 on climate change and carbon neutrality, actual reductions should precede compensation activities (ISO, 2023). The MFCA 2.0 method represents an effective tool to realize the calculated reduction potentials. It helps companies to take steps that make their production processes more resource efficient, thereby reducing the environmental impact of the company and the industry. Finally, MFCA 2.0 represents a method that contributes to the fulfilment of one of the goals of industrial ecology, which is the support of corporate decisions regarding the reduction of environmental effects (Lifset & Graedel, 2002).

MFCA 2.0 with its consulting concept is an organization concept of high relevance for today's sustainability challenge. It is not a temporary fashion, how Kieser (1996) would perhaps critically question the method. He finds that there are organizational fashions that are in fact myths and which therefore may not prove useful to managers (Kieser, 1996). Following Rummel's (1936) line of argumentation, materials management—and hence also MFCA—is "more than a fashion" [own translation][38] (p. 222). MFCA is rather a promising rebirth of the method to develop more of its potential. The global sustainability challenge includes environmental, economic and social aspects, and MFCA 2.0 offers a practice-oriented response combining environmental and economic goals. Since the concept of sustainability is not a temporary fashion, but an imperative requirement, MFCA 2.0 is a future-oriented method. This represents an opportunity for companies and whole industries to take entrepreneurial responsibility. They can assume a pioneering role for industrial businesses that aim to protect the global climate. A country's high dependence on raw material

[38] Own translation, original in German: "mehr als eine Mode" (Rummel, 1936, p. 222)

imports can be transformed into a business opportunity that increases its future competitiveness as well as the competitiveness of many industries and innumerable companies.

6.2 Challenges, Limitations, and Further Research Opportunities

Addressing challenges, limitations and further research opportunities, the following aspects can be noted. First, the new MFCA 2.0 concept may not be understood immediately. The scenario-based approach and the resulting improvement potentials require a certain amount of time and intellectual work. Moreover, prior knowledge about MFCA 1.0 could even have counterproductive effects. Although the two approaches may seem similar at first sight, they pursue different goals. In MFCA 2.0, material losses play a different role as the new algorithm aims at the evaluation of their reduction and not on the evaluation of the losses themselves.

Second, when building the model, it is important to deliberately define the relationships between different parameters. Generally, the quantity centers of an MFCA 2.0 can depict any mathematical function. However, it represents a challenge to define them correctly since it requires detailed knowledge of the real process conditions and the context, which is why most MFCA models are based on linear functions as default relationships. This may be a simplification of reality. To avoid this, a certain amount of knowledge of the processes and MFCA modeling experience are required, which can represent a challenge to an organization.

Third, the question of how to find data to build the model may be difficult to answer in many cases. Consequently, the biggest challenge may be related to the data required to build the model. The three data requirements are availability, accuracy and appropriateness. As especially Case Study 2 showed, data can be available in large amounts. However, this does not imply that the data that is available is also accurate and appropriate. That depends on the goal and scope that were defined at the beginning of the MFCA 2.0 application. As Case Study 1 showed, the data demand depends on the question that is being investigated. For example, to quantify a specific saving potential, only the data points in which the two scenarios differ from each other are required. Once the data points in which the scenarios do not differ are determined, the data collection can be shortened and thus simplified.

The data for the GHG emission factors can be taken from environmental databases such as Probas (Federal Environment Agency of Germany, n.d.), Ecoinvent (2022), GaBi (Sphera Solutions GmbH, n.d.) or many others on the growing market for GHG emission data. This is an advisable first step, but it is important to keep in mind that their use may limit the meaning of the MFCA results. The data that was collected by the company itself or that was collected and provided by a supplier should always be compared and, depending on the results, it should be evaluated if the conditions of the data collection are more appropriate for the use in the specific MFCA 2.0 application. These analyses and decisions require expert knowledge and can thus possibly present a challenge, demanding additional qualifications or consulting services.

When addressing the three challenges that were just mentioned, a corporate master data repository should be considered. As the reduction of environmental emissions and an increase of resource efficiency go hand in hand, a corporate data repository offers manifold and lasting advantages. In this way, different employees working with different methods such as LCA, MFCA, Six Sigma or lean management can enter, access and monitor the data at the same time. The repository can be used for different methods that have overlapping data requirements although they each require different calculations. In this way, the different methods MFCA 1.0 and 2.0, LCA and lean management, and perhaps even further methods using the mentioned datasets move closer together. They could access and communicate via the same data repository, leading to synergy effects and improved quality of the data over time. Moreover, audits and certifications such as an environmental product declaration (EPD) or an ISO certification become easier to obtain. In conclusion, the building and maintenance of a corporate master data repository offers many advantages that pay off in various ways over time.

Data is often a snapshot of a certain period that usually lies in the past. Therefore, it should be ensured that the MFCA 2.0 analysis is based on most recent data or real-time data, if possible, depending on measurement capabilities. Moreover, as Kilger (1993) remarked, although a mathematical model that is based on data from the past has value for forward-looking decisions to a certain extent, a well-informed decision additionally requires non-calculable information and knowledge. Therefore, the most comprehensive model built by experts will not be sufficient, although it is certainly useful (Kilger, 1993). This is where the consulting concept comes into effect as it defines the purpose of consulting and comprises qualitative success factors such as responsibility and controllability (cf. Chapter 5).

If the application of MFCA 2.0 addresses a company's supply chain, the following three aspects should be considered because otherwise, they could limit the method's positive effect. First, the will to improve the resource efficiency of the supply chain should be stated by all participating companies at the beginning of the cooperation. This will increase the sense of commitment and hence increase the cooperation's prospect of success. Second, it is important that the companies involved have a trust-based relationship on which effective cooperation can be built. This may require non-disclosure agreements or other ways to meet the needs for security of different parties. It is advisable to discuss and determine these framework conditions from the beginning to avoid delays or misunderstandings. Third, data exchange, preparation and processing are necessary and sometimes time-consuming process steps. For example, some process steps require personnel capacity including response times and times for the clarification of questions. These are helpful aspects to be considered when planning the MFCA 2.0 application along a supply chain.

The Corporate Sustainability Due Diligence Directive (CSDDD) is a legal framework by the EU that addresses a company's operations including its value chains. It was adopted in 2022 as proposal by the European Commission (n.d.) and approved by the Council of the European Union in May 2024. It requires the EU's member states to implement the CSDDD into national law by July 2026 (European Commission, n.d.). The Directive represents a step towards transparency and due diligence for the protection of human rights and the environmental effects of economic activities (European Commission, n.d.). Companies falling under the scope of the Directive are required to look at their upstream and downstream supply chains including raw materials. They need to address different topics such as the end of the life of their products, report the results and take specific action (European Commission, n.d.). The CSDDD is a political step towards sustainable development, and it also prepares the ground for the implementation of MFCA 2.0 along supply chains. This aspect could be further researched to work out synergy effects.

In conclusion, the combination of the quantitative MFCA 2.0 algorithms—on which the model is built—and the qualitative consulting concept opens new perspectives to manufacturing companies. It creates a lasting incentive to develop and implement improvement measures, e.g., through a suggestion scheme (Patzak, 1982; Japan Human Relations Association, 1997; cf. Sections 5.4 and 5.5). This is no guarantee for an actual increase in resource efficiency since it needs to be tailored to the company-specific situation. Its effectiveness depends on different factors such as employee involvement and commitment, management support and data availability. For a successful and lasting implementation, the integration of MFCA on a strategic level is required, as two studies on the application of MFCA in practice conclude (Kitada et al., 2022; Rieckhof et al., 2015). MFCA 2.0 will develop its full potential only if it is anchored in the corporate strategy and practiced across the different employee groups from management to plant operators. These different aspects can be understood as limitations at first sight, or as challenges demanding further research. For example, case studies and best practices can provide guidance to companies that would like to implement the method in the long run and along their value and supply chains. Moreover, the VDI developed and published the standard VDI 4800 Part 1 containing principles, strategies and measures that offer impulses and examples of how to implement the concept of resource efficiency in a company (VDI, 2016). This standard could be examined in light of MFCA 2.0 to specify and include the method as a resource efficiency method.

MFCA 2.0 is undoubtedly a powerful method to increase the resource efficiency of a production process or supply chain. The challenges, limitations and research opportunities that were named in this section are of high relevance for the method. If the method is implemented poorly, this may cause adverse effects such as demotivation or additional material and energy losses, leading to even higher environmental and monetary burdens. Resource efficiency always pursues an increase of the benefit or a decrease of the effort related to a good or a service (VDI, 2016, cf. Section 1.3).

Ultimately, resource efficiency alone will not solve the sustainability challenge. As mentioned in Section 1.2, a combination of different sustainability strategies is required (Pufé, 2017). For example, the sufficiency strategy approaches the topic from a different angle by addressing and reducing excess consumption (Princen, 2005). The two concepts supplement each other and in combination, they point the way towards sustainable development in the future (Princen, 2003). This view beyond the horizon should be kept in mind when discussing different aspects of sustainability strategies and methods.

6.3 MFCA 2.0 for Sustainable Development: Resource Efficiency and the Meaning of Raw Materials

With its focus on the increase of material and energy efficiency, MFCA 2.0 contributes to the sustainable development of the manufacturing industry. Against the tendency in the literature aiming at the implementation of MFCA 1.0 and providing case study examples across different industries and countries, this dissertation suggests a novel approach. It has developed the method from an analytical method that creates transparency to an action-oriented method that supports the development, evaluation and implementation of improvement measures including existing or potential material loops in the system under analysis.

So far, MFCA as a method is not widespread yet (cf. Section 3.5, e.g., Christ & Burritt, 2015; Günther, Rieckhof, et al., 2017; Günther, Rieckhof, et al., 2017). Its use in industry becomes more appealing through the consulting concept that has been developed in this dissertation. The consulting concept takes a holistic approach starting from the purpose of consulting based on MFCA 2.0 (cf. Section 5.1) and it provides guidance for the search for improvement measures (cf. Section 5.4). It also includes an explanation of how MFCA 2.0 can be used in the long term (cf. Section 5.5). Moreover, the roles of data (cf. Section 5.6) and the MFCA 2.0 model (cf. Section 5.7) are clearly defined. This methodological advancement fosters the application of the method, leading to multiple positive effects through increased resource efficiency and reduced raw material demand as a result. The effects represent a competitive advantage and contribute to the continued existence of a company, its industry and a country's economy.

Taking a global perspective, it has already been pointed out in Section 3.5 how the method of MFCA contributes to the SDGs *6 Clean water and sanitation*, *7 Affordable and clean energy*, *12 Responsible consumption and production* and *13 Climate action* (UN, n.d.; Kokubu et al., 2023). The methodological advancement achieved with MFCA 2.0 enhances the method's contribution to the mentioned SDGs. It points the way to take action against climate change and other hazards to humankind and the environment.

SDG 12 strives to reduce the GHG emissions related to production and consumption (UN, n.d.). With its focus on potential improvement measures, MFCA 2.0 enables the evaluation and comparison of measures regarding resource use, GHG emissions and monetary costs. Additionally, it allows the monitoring of resource efficiency indicators such as the development of waste quantities, e.g., in absolute and relative values, over time. In this way, the method provides specific and tangible instructions to make a production process more sustainable based on loss reductions and recycling activities such as material loops (cf. Subsection 4.3.5). Their impacts are to be verified and quantified with the scenario-based approach, on which MFCA 2.0 is built. Moreover, the method encourages and supports the different targets of the goal in a corporate context, such as the sustainable and efficient use of natural resources (target 12.2) and the reduction of waste through prevention, reduction, recycling and reuse (target 12.5). MFCA 2.0 is also suitable for specific types of waste and their corresponding industries, such as food waste (target 12.3) or chemical waste (target 12.4). Target 12.1 focuses on the implementation of a framework enabling more sustainable consumption and production, and it differentiates between developed and developing countries (UN, n.d.).

MFCA 2.0 can also support Germany in meeting its responsibility as industrial and export country. The country's industry and political representatives can promote the improved method on different platforms and markets. For example, German companies acting on an international level such as multinational enterprises can play a pioneering role. This will encourage companies to adopt sustainability practices and reporting, thereby contributing to the fulfilment of target 12.6 (UN, n.d.). When presenting and advertising the MFCA 2.0 method, it is important to explain that it is not an end in itself. MFCA 2.0 detects losses and quantifies potential savings based on loss-reducing measures. However, the choice for and the implementation of the measure(s) remain tasks of the person(s) responsible for the processes, who find guidance in the consulting concept.

Additionally, MFCA 2.0 addresses SDG 8, which promotes, inter alia, sustainable economic growth and productive employment (UN, n.d.). However, the UN's most recent progress report at the time of writing this dissertation states that in 2022 and 2023, productivity growth remained at an alarming rate below 0.5% (United Nations General Assembly Economic and Social Council, 2024). According to the report, this endangers the positive development of the global economy because productivity growth is an important influence factor for growth (United Nations General Assembly Economic and Social Council, 2024). Through the implementation of MFCA 2.0 in companies across different industries, losses can be gradually reduced, which in turn increases resource efficiency and thus fosters productivity growth.

Various political activities can promote the dissemination of the method. As has been shown in the analysis of *Kilger's Flexible Standard Costing and Contribution Margin Accounting*, the association AGPLAN substantially contributed to the success of the new approach (cf. Paragraph 2.2.1.4). In the US, the organization N.A.C.A.—later renamed NAA—was an important platform for the cost accounting discipline (cf. Subsection 2.4.6). It supported its development by offering a platform for exchange and discussion, and the organizations functioned as a bridge from theory into practice by offering trainings and public conferences to researchers and industry representatives alike, also on an international level. In this way, they provided incentives to implement the method in companies across different industries.

Applying this knowledge to MFCA 2.0 and its consulting concept, such incentives can be consulting services and training programs free of charge thanks to public funding on the one hand. On the other hand, political activities can also comprise legal instruments such as documentation requirements and reporting obligations regarding resource use and material losses within a company or along its supply chain. Subsection 5.2.8 elaborates more on the question of how the dissemination of MFCA 2.0 and the consulting concept can be fostered and accelerated. Such activities can be embedded in a larger framework such as Germany's Resource Efficiency Program (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany, BMU, 2020), activities on the European level such as the CSDDD (cf. Section 6.2, European Commission, n.d.), or the Circular Economy Action Plan (European Commission, 2020).

An example of a legal measure can be found in France. In France, food waste caused by supermarkets larger than 400 m^2 was prohibited by law known as the "loi Garot" (Ministère de l'agriculture et de la souveraineté alimentaire, 2024). It was passed in 2016, and France was the first country in the world to pass a law against food waste. The law's positive effects have been proven, leading to cooperations between supermarkets and food aid associations, new measures such as employee training programs and promotional strategies that reduce food waste (EY, 2019). This law and further legislative decrees have demonstrated the impact national legislation can make (Ministère de l'agriculture et de la souveraineté alimentaire, 2024; Zentrum für Europäischen Verbraucherschutz e.V., 2023). Interestingly, in China, an anti-food waste movement was initiated by the population, and it paved the way for the legal measure of the "Anti-Food Waste Law" (Feng et al., 2022). In China, this law addresses the catering industry, and it was adopted in April 2021 (Feng et al., 2022).

Generally speaking, legal regulations are an effective policy instrument. Nevertheless, their effect is limited, and legal regulations are one part of the solution. A combination of different measures can avoid the use of legal loopholes. This comprises additional instruments which create incentives for market participants such as employee training programs or the initiation and support of cooperation activities between different actors. Moreover, civil society can play a decisive role in the reduction of losses and sustainable development, as the example of China has shown. It can foster acceptance of socio-economic responsibility carried by the different actors, which can be accompanied or nudged with legal regulations.

In conclusion, this section summarized how the novel approach of MFCA 2.0 and the related consulting concept can increase a company's resource efficiency and thus make a contribution to sustainable development of the economy. Through a permanent reduction or even elimination of material losses in a production process, raw material demand, GHG emissions and financial costs can be reduced. These reductions, in turn, bring about an increase in the resource efficiency of the process under analysis. This includes the evaluation of raw material loops that already exist or are being considered. In this way, an increase in the extraction of raw materials including the consequent negative effects can be avoided, and sustainable development will be accelerated. Sustainable development is specified and set by the UN (n.d.) with 17 SDGs including different targets, and MFCA 2.0 and the related consulting concept can practically contribute to the achievement of SDGs 6, 7, 8, 12 and 13. In combination with additional policy measures such as free services, training programs and appropriate legal instruments, the research results of this dissertation can make a positive impact on a company, an industry and the overall economy.

7 Conclusion: The Need for Action for Sustainability

Actions speak louder than words.—English proverb

MFCA 2.0, which was developed in this dissertation, is a method that can systematically reduce raw material demand, increase resource efficiency, and thus accelerate sustainable development. The concept of sustainable development includes specific metrics, tangible indicators and quantifiable goals—such as those defined in the SDGs by the UN—which, in turn, require user-oriented, effective methods and tools. MFCA 2.0, in combination with the related consulting concept, represents such a user-oriented, effective solution. With its focus on the identification and quantification of inefficiencies in the form of losses, MFCA generally represents a promising approach, since material losses are usually not in a company's focus (cf. Chapter 3). Physical losses can imply high environmental and monetary losses, depending on where they occur in the value chain, because their processing already required investments in the form of energy, system and waste management costs. Therefore, they entail significant saving potentials that should be uncovered, analyzed and used in collaboration with the respective process owners in the company. The approach follows the simple and straightforward principle that a reduction of losses in a process means an increase in resource efficiency in return.

The literature shows that MFCA is not very popular in practice and that it has not become widespread yet (cf. Section 3.5). One reason is the lack of integration into existing management concepts. Moreover, it does not lead to an actual reduction of losses. Instead, MFCA focuses on the assessment of losses and it does not provide guidance and support for the necessary subsequent steps (cf. Sections 3.5 and 3.6). In this regard—although the analysis of losses is undoubtedly a correct and promising starting position—the method has greater potential for corporate application. This concerns, for example, the PDCA cycle included in the standard ISO 14051 (ISO, 2011). However, the cycle requires all four steps to be completed. According to this standard, MFCA does not ensure a reduction of losses, thereby neglecting the last act step. It also presupposes linear relationships between the different flows in the MFCA model and in the MFCA calculations. Moreover, the method lacks support regarding the search for improvement measures and the calculation of the saving potential of the different improvement measures.

This dissertation was motivated by these aspects, and its aim was to improve the method. With the improvement of the method embodied in MFCA 2.0, loss-reducing improvement measures can be evaluated with the scenario-based approach (cf. Section 4.1). The resulting saving potentials make the method much more action-oriented. MFCA 2.0 results provide concrete support regarding the decision for one or multiple improvement measures and the subsequent implementation thereof (cf. Chapter 4). In this way, the PDCA cycle—as described in the standard ISO 14051—is completed and the method can unfold its potential. This methodological improvement was based on the history of cost accounting (cf. Chapter 2). "Riebel's Generic Direct Costing and Contribution Margin Accounting", which he wrote in the 1950s and published in 1959 (cf. Section 2.5), turned out to be particularly useful. It delivered valuable impulses for the development of the new measure-centered MFCA approach. Riebel (1994b) and Kilger (1993) led an intensive dialogue over many years, thereby continuously challenging each other. Although the critical feedback from each other did probably not lead to enthusiasm at first, it fueled a worthwhile refining of their cost accounting theories over the years.

Additionally, this dissertation was inspired by historical aspects of the cost accounting discipline. Cost accounting has always strived to offer quantitative information that supports and improves corporate decision-making. Schmalenbach (1899, 1907/1908, 1934) had already expressed important ideas about fixed costs, which then led Rummel (1934) to develop *block cost accounting*. Later on, Rummel (1936) suggested mass balances and analyzed the connections between material flows and losses in order to improve decision-making regarding the production process including machines and materials. This approach was recognized and resumed at a later time, leading to new forms of cost accounting.

These previous findings were also used to improve the MFCA method. The untapped potential of the method was first identified and then implemented, leading to MFCA 2.0. Just like the history of cost accounting continued to evolve over time, the MFCA method is not a definite and fixed tool. It has been and still is developing over time, and it continues to evolve in response to different experiences, requirements, and economic trends.

While MFCA 1.0 quantifies the values of the losses, MFCA 2.0 is now able to quantify the actual saving potentials as a result of loss reductions. This gives MFCA results new relevance, as they offer a solid basis for corporate decision-making processes. Furthermore, since MFCA 2.0 is based on improvement measures, it fosters the development of improvement ideas, innovation and new green technologies that reduce losses and thus increase process efficiency (cf. Section 5.4). In other words, MFCA 2.0 identifies and addresses the root causes of losses. It does not strive for end-of-pipe solutions. Moreover, MFCA 2.0, with its scenario-based approach, can evaluate material loops that recirculate material losses back into the process analyzed (cf. Subsection 4.3.5). Depending on the results and the alternative improvement measures that are available, recirculation can be either a worthwhile measure or there is a more suitable alternative, depending on the criteria that apply to the specific decision situation and context.

With the consulting concept related to MFCA 2.0, the improved method can be integrated into corporate practice, leading to greater transparency regarding resource management and other sustainable practices, thus enabling cost accounting for sustainability. The consulting concept pursues a specific purpose, and it focuses on losses by documenting, planning and analyzing them. It thereby creates transparency for the company (cf. Sections 5.1 and 5.2). Communication, controllability and responsibility are further elements of the MFCA 2.0 consulting concept (cf. Subsections 5.2.5 and 5.2.6). The role and working method of the consultant team—if the case of a consultancy situation applies—are also addressed (cf. Section 5.3). Moreover, the concept discusses what an adequate improvement measure looks like (cf. Section 5.4). It empowers a company's employees to strive for improvements, strengthens their team spirit and thus provides a basis for continuous improvement (cf. Section 5.5). Continuous improvement can be supported through measures such as good documentation, a positive mindset concerning errors and mistakes, and the integration of MFCA 2.0 into cost accounting systems. This ensures the lasting use of MFCA 2.0 and the method's results in a company. Finally, the role of MFCA 2.0 data and the MFCA 2.0 model were discussed (cf. Sections 5.6 and 5.7). Chapter 5 closes with two case studies including specific application examples, which illustrate challenges and practical learning experiences related to the new methodological approach (cf. Section 5.8).

In summary, MFCA 2.0 is a highly flexible, effective and empowering tool that can be applied to numerous different process technologies and production methods. Besides financial aspects, the method addresses resource depletion, climate change and other negative environmental effects of business activities such as manufacturing processes. Depending on the availability and quality of data (cf. Section 5.6), MFCA 2.0 enables the analysis and comparison of different improvement measures regarding resource use (physical values of material and energy, e.g., kg and kWh), environmental emissions (e.g., kg CO_2e) and monetary costs (e.g., EUR). The approach demonstrates that the environmental and monetary dimensions can be treated using the same methodology because they are based on the same algorithms. The only difference lies in the factors and units that are for the calculations. For example, the monetary dimension uses cost factors or purchase prices, whereas the environmental dimension uses emission factors. When analyzing alternative courses of action, MFCA 2.0 offers a valuable perspective that can be used for informed corporate decision-making.

The MFCA 2.0 approach that was developed in this dissertation will be illustrated with a simple application example. It assumes that a company can reduce its waste production of a certain material such as steel by 2 kg per product unit. This reduction can be achieved across the analyzed production process, for example, by implementing a near-net-shape production method as an improvement measure. As a result, the company's material demand for steel is reduced by 2 kg per product unit. Assuming a mass-dependent electricity demand in the production process of 3 kWh/kg, 6 kWh electricity can be saved per product unit. These two physical values—2 kg of steel and 6 kWh of electricity—can then be multiplied with the GHG emission factors (1.6 kg CO_2e/kg steel and 0.4 CO_2e/kWh electricity) and corresponding purchase prices (2.0 EUR/kg steel and 0.4 EUR/kWh electricity), yielding the environmental and monetary saving potentials presented in the following Table 24.

Table 24: Saving potentials of an exemplary improvement measure based on MFCA 2.0

Saving potentials of exemplary improvement measure			
Input	Physical resource use	GHG emissions	Monetary
	kg or kWh	*kg CO_2e*	*EUR*
Steel	2.0 kg	3.2	4.0
Electricity	6.0 kWh	2.4	2.4
Total		5.6	6.4

Assuming an annual production volume of 1,000 product units, the saving potential totals to 2 tons of steel, 6,000 kWh, 5,600 kg of CO_2e and 6,400 EUR per year, respectively. These numbers are fact-based arguments in favor of the improvement measure, and they can now be evaluated against the investment cost and alternative improvement measures (cf. Paragraph 4.3.4.10).

These aspects are important considerations for a company's sustainability strategy because the global competition for raw materials is becoming increasingly important. A company's future competitiveness will be defined by the three dimensions of resource dependence, the environmental emissions caused by its business activities and its profitability. As illustrated in Section 1.4, the EU's trade balance for raw materials was –49.1 B EUR—the highest deficit in the period between 2013 and 2023 (cf. Section 1.4; Eurostat, 2024). Germany's economy is highly dependent on imports, especially regarding energy and metals (cf. Section 1.4, Table 1 and Table 2; BGR, 2024, pp. 21f.). In light of this situation, an efficient and responsible raw material use is imperative for the long-term viability of a production company. MFCA 2.0 offers a competitive advantage by enabling not only cost reductions and profit increases, but also a reduced dependence on raw materials and energy, and reduced impacts of corporate activities on the environment.

This study advances the understanding of resource efficiency by integrating environmental and economic goals, and it emphasizes the relevance of resource efficiency methods such as MFCA. Due to a lack of effective methods in the field of environmental management that are available to companies in the manufacturing industry, there is a need for methods that systemically approach the subject. They emphasize the urgency of cleaner production to pursue economic and environmental sustainability. Such methods should provide informed decision-making support and lead to resource efficiency-increasing measures that prove effective in practice. MFCA 2.0 and the related consulting concept provide such a solution. Therefore, the results of this work are highly relevant for the manufacturing industry with its dependence on raw materials and energy resources.

As discussed in Section 6.2, there is a need for further research on education, training, action-based research, and exchange of experience. These need to be promoted and financially supported in different forms. Well-meant advice and case studies focusing, for example, on different industries, technologies and regions may have a greater impact than theoretical discourse or a moral imperative. Such further research activities can build on the present work by, for example, applying the MFCA 2.0 method to different industries and technologies. These research activities can then reduce industry- or technology-specific barriers with regard to the method in particular or the topic of resource efficiency in general. Furthermore, the dissemination and the following continuous application of the method require political and financial support such as state subsidies in response to intensifying global competition. Additional research will be helpful in order to apply these political instruments effectively (cf. Section 6.3).

While further research is needed, as described above, the urgency for action continues to grow because the environmental and industrial conditions continue to worsen. Therefore, it is time-critical to put the results of sustainability research into practice. Resource depletion, climate change and other negative environmental effects are global challenges, requiring global efforts and local solutions. With a view to the future, these aspects will be of growing importance because they are intertwined. Innovative companies, political actors and decision-makers can lead by example and measurably contribute to sustainable development with active reductions of losses and other production inefficiencies. They should use the opportunity to measurably contribute by using effective methods and tools and by distributing them in their industries and networks. It is high time for active action, not just lip service. Resource-efficiency tools like the MFCA method—which was refined to MFCA 2.0 and complemented with a consulting concept in this dissertation—serve as essential and pioneering instruments on the journey towards a more sustainable future that respects our planet and considers the needs of humanity.

8 References

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