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Shared benefit by Material Flow Cost Accounting in the food supply chain – The case of berry pomace as upcycled by-product of a black currant juice production

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A B S T R A C T

Berry fruits such as black currants are known to have health-promoting effects as they contain high amounts of phytochemicals (polyphenols, anthocyanins) and dietary fibers concentrated in the peel and seeds. So far, the berry pomace by-product obtained from the production of berry juice is mainly subject to incineration and less recognized by companies as an opportunity to create additional value. Material Flow Cost Accounting is a powerful tool when it comes to the identification of resource inefficiencies in production systems and can provide useful information as an ad-hoc analysis supporting investment decisions, such as the extension of the product portfolio. This study investigates the material efficiency potential of a black currant juice production in Germany while considering potentials for cost reduction, revenue generation, and carbon dioxide mitigation resulting from the avoidance and upcycling of food waste. We used Material Flow Cost Accounting in combination with carbon footprinting and probabilistic scenario analysis to examine the subject. The analysis showed that, in terms of the global warming potential, the environmental performance of the main product, black currant juice, benefits from the upcycling of the pomace to a marketable product. From the economic side, we could not demonstrate a reasonable amortization of the additional investment costs. However, the scenario and uncertainty analysis revealed promising optimization strategies which would lead to an increase in profit of about 13%: first, additional use of apple pomace and second, the production of high-quality, organic pomace to achieve a selling price of at least €2.00/kg as a functional food supplement or in pharmaceutical and cosmetic applications.

1. Introduction

From a nutritional point of view, fruits are a highly complex and diverse food group. Their content of different carbohydrates, minerals, vitamins, pigments, enzymes, oils, amino acids, and further phytochemicals is the reason for their variety of tastes and manifold health aspects and, thus, makes them an important part of our daily diet (Lozano, 2006). Berry fruits, in particular, such as black currants (*Ribes nigrum* L.), are known to reduce the risk of cardiovascular diseases and cancers as they contain high amounts of phytochemicals with antioxidant and anti-inflammatory properties (Mazzoni et al., 2016). They are rarely consumed fresh, instead being industrially processed to juice, syrup, or jam.

Since 2003, the European black currant (BC) sector suffered from overproduction, low market prices, and a lack of innovation (Duponcel, 2007). Meanwhile, health and lifestyle trends are significant challenges, requiring beverages to contain less sugar, be produced organically or vegan, and be offered in smaller packaging sizes (AIJN, 2018). In addition, transformation to more sustainable production systems has become a decisive competitive factor for BC producing and processing companies. This includes measures for food waste prevention as acknowledged by UN Sustainable

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Development Goal (SDG) 12.3[1] (UN, 2015), the EU action plan for the Circular Economy (EC, 2015a), and under the term 'bio-waste' as defined by the EU Waste Framework Directive (EC, 2008). So far, the by-product pomace obtained from the production of black currant juice is mainly subject to thermal energy recovery. Depending on the regional infrastructure and established waste management practice, BC pomace is also composted or fed to farm animals. However, material utilization as soil fertilizer, animal feed, or substrate in biogas production is less desired or only in small amounts due to the pomace's acidity and microbial viability. It is these properties that could lead to a disturbance of the delicate microbiological environment in a biogas reactor; in soil, the acidity could cause a reduction of the pH value and thus a mobilization and introduction of so far fixed pollutants, e.g. heavy metals and pesticides, into groundwater.

Several studies highlight the opportunity of increasing company revenues if berry pomace is no longer seen as a by-product but further processed to value-adding food ingredients, and thus contributing to food product innovation (Anderson et al., 2014; Rohm et al., 2015). This is grounded in observations of changing consumer lifestyles and growing interest in a sustainable, health-promoting, and natural nutrition. BC pomace is particularly interesting thanks to its high amounts of bioactive compounds (polyphenols, anthocyanins) and dietary fibers concentrated in the peel and seeds. In addition, berry pomace is comparatively less contaminated with pesticides given good agricultural practice (Ortelli et al., 2004; Struck et al., 2016). Multiple applications are conceivable, for instance, in functional food (baking products, cereal-based snacks, or smoothies), pharmaceuticals, or cosmetics. This requires rapid processing or stabilization of the pomace, which would spoil very quickly under ambient conditions due to its sugar and water content (Reißner et al., 2019; Tournas and Katsoudas, 2005). The pomace is typically deep-frozen at a minimum of $-20\,^{\circ}$C (Struck et al., 2016). Optimum milling and drying conditions for converting berry pomace into a dry powder product were investigated in a review by Struck et al. (2016), in which the moisture content, drying time, and temperature range above $60\,^{\circ}$C were identified as being critical for the preservation of heat-sensitive compounds.

The valorization potential that lies in food waste is often not recognized by decision makers, where doubts over solid business cases persist (Hanson and Mitchell, 2017). A higher awareness and quantification of the associated costs of food waste and the possible revenue of upcycled by-products could help decision makers to justify the necessary investments in already available extraction and concentration technologies (Pap et al., 2014; Struck et al., 2016). Moreover, the possibility to lessen the environmental burden of the primary product juice if berry pomace is used as a substitute for macronutrients (e.g. fibers replacing sugar, flour, or fat in dough[2]), is rarely recognized.

Traditional accounting practices do not include adequate environmental information (Guenther et al., 2015; Jasch, 2009) and are therefore very limited in their ability to support awareness of the environmental implications of business operations. Material Flow Cost Accounting (MFCA) tackles exactly this problem and aims to improve both the environmental and economic performance of producing or service-oriented organizations (METI, 2007). By allocating all costs in a production system not only to the final product but also, based on fair assumptions, to the non-product output (production losses, waste), cost saving potentials can be revealed that have, thus far, remained unseen by decision makers. Because the material purchase value of waste can exceed the disposal costs by a multiple (Jasch, 2009; Schmidt, 2015), improving an organization's economic performance through resource use optimization and waste minimization is a logical strategy. In addition, an increased resource efficiency is associated with lower environmental impacts in upstream supply chains and thus leverages the improvement of an organization's environmental performance. Empirical studies concluded that about 90% of the environmental expense of an organization can be caused by costs related with a non-product output (Christ and Burritt, 2015; Gale, 2006; Jasch et al., 2010; Jasch and Danse, 2005; Jasch and Lavicka, 2006). On another level, MFCA supports the inclusion of a life cycle perspective when investigating the supply chain and end-of-life of a product (Schrack, 2014) and creates synergies by integrating the vantage points of different stakeholders (engineers, environmental scientists, economists, knowledge managers, and strategic managers) (Guenther et al., 2015; Rieckhof et al., 2015).

Despite these arguments, after 20 years of existence, MFCA is rarely used in practice and more subject to conceptual research work or action-based case studies (Christ and Burritt, 2015). Decision makers are not aware (or convinced) of the benefits of MFCA and stick to traditional accounting systems or combine them with other environmental management accounting (EMA) tools (Kokubu and Kitada, 2015; Lang et al., 2005). According to Kokubu and Kitada (2015), MFCA can also conflict with existing management perspectives that are rather oriented around financial indicators and show weaknesses in the controllability of production losses. Rieckhof et al. (2015) emphasize that MFCA first has to be interlinked with an organization's management control system to translate its overarching goal of resource use optimization into corporate strategy. However, even if companies are informed and incentivized by MFCA promotion programs, as was the case in Japan at the turn of the millennium, many of them used MFCA only for a single cost study and not regularly (Onishi et al., 2008). As if that were not sobering enough, companies applying MFCA of their own accord or, more likely, in cooperation with researchers are reluctant to provide data, publish cost saving results, or share their experiences (Guenther et al., 2015).

As a consequence, MFCA lacks empirical evidence in many domains, such as key drivers and barriers for the implementation in practice, dissemination in different sectors and organizations, framework conditions in different countries, etc. (Christ and Burritt, 2015). Furthermore, comparability and interoperability with other management and accounting tools and information systems have been identified as relevant for a successful implementation of MFCA and worthy of further investigation (Lang-Koetz et al., 2006; Rieckhof et al., 2015). In Guenther et al. (2015) they propose adapting MFCA models to sector-specific applications and connecting physical flows with CO_2 emissions as demonstrated by Schmidt (2015). When considering the combination with life cycle assessment (LCA), Schrack and Prammer (2013) see a solution which allows for the integration of externalities into MFCA. Moreover, the mapping of multi-product systems and application of more advanced statistical analysis are discussed in the scientific MFCA community (Christ and Burritt, 2015; Schmidt, 2015).

The aim of this paper is to investigate the material efficiency potential of black currant juice production in Germany while considering potentials for cost reduction, revenue generation, and carbon dioxide (CO_2) mitigation resulting from the avoidance of food waste and recovery of valuable ingredients retained in the

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[1] Yearly food waste is estimated to account for 1/3 of global food production corresponding to 1.3 billion tons. By 2030, per capita global food waste at retail and consumer levels should be halved and losses in production and supply chains reduced.

[2] It must be noted that pomace cannot replace the functionality of individual macronutrients since pomace in the baking product can have a different function. Therefore, it may not be possible to replace just a single macronutrient in the process, as it would be necessary to replace all three proportionately.

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pomace. Our analysis represents the first integrated assessment of the environmental and economic performance of upcycled food waste from a berry juice production. It focuses on applying and adapting MFCA by taking industry-specific and geographical aspects into account and thus contributes to the second MFCA research stream as presented in Schaltegger and Zvezdov (2015). According to Udo de Haes et al. (2004), our approach can also be considered as an extension of the LCA concept as MFCA and LCA are based on a fully consistent model and refer to the same functional unit, but also as a hybrid analysis as the findings were later utilized in a statistical analysis. The paper contributes to the ongoing discussion in the MFCA community as it demonstrates the scientific and practical feasibility of a combined approach, and, moreover, shows how companies can benefit from implementing strategies that help avoiding food waste in the production.

The article is structured into five sections. Following this introduction, the conceptual approach of MFCA is presented in section 2 before the scope and concrete methodology of the case study are described in section 3. Results from MFCA and carbon footprinting, including the outcome of uncertainty analyses (scenario analysis, Monte Carlo simulation, and pedigree-matrix), are presented and discussed in section 4. Section 5 concludes this article.

2. Conceptual approach of Material Flow Cost Accounting

MFCA is a management tool that integrates physical and monetary information about the manufacture of a product in order to support informed decision making within the organization and along the supply chain (ISO, 2011, 2017). The meanwhile standardized methodology originally emerged from environmental management accounting (Jasch, 2009) and is rated among the most promising and sophisticated EMA tools (Christ and Burritt, 2015; Kokubu and Kitada, 2015). According to Schaltegger and Wagner (2005), it directly and indirectly shares principles with ecological economics, management accounting and cleaner production. Moreover, MFCA is considered as an advancement from the *lean production approach* well-established in the automotive sector (Ōno, 1988). Besides the intensive research of its theoretical foundation, it is already applied in practice in Japan, Germany, and emerging countries (Guenther et al., 2015).

MFCA allows for the systematic identification and quantification of material flows (raw materials, operating materials), material stocks, and energy flows in a production system based on physical units. As opposed to traditional cost accounting where the total production costs are borne by the final product alone, MFCA distinguishes between costs attributable to the final product and costs concealed in material losses (waste, emissions, and wastewater) (ISO, 2011). Hence, MFCA can provide transparency regarding the origin of waste management costs of complex production processes and can determine the actual product costs in a zero-waste scenario (Schmidt, 2015). It can be assumed that organizations are more willing to change their production and procurement practices when the true proportionate cost of material losses in the final product becomes evident. In this way, MFCA contributes not only to exploiting cost reduction and resource efficiency potentials in individual segments of the production system or entire supply chain, but also to mitigating environmental burdens (ISO, 2011). This includes the identification of alternative materials with an advantageous economic or ecological profile and the adoption of advanced waste management solutions.

The development of a material flow cost model is similar to a material flow models used in LCA, since in both cases the material flows are determined in physical units and related to a reference unit such as kg, m^3, or kJ. Thus, a simultaneous calculation of environmental impacts (e.g. global warming potential) and costs is possible if, for example, kg-related emission factors are substituted by kg-related prices (Schmidt, 2011, 2015). Such an integrated approach and the development of advanced software solutions is deemed decisive by Schmidt (2015) in making the use of MFCA more interesting for companies.

The successful implementation of MFCA requires the organization to systematically carry out all necessary activities. Useful guidance is provided by the PDCA (Plan-Do-Check-Act) cycle as given in ISO (2011), which was amended by the authors to include the carbon footprint similar to Rieckhof and Guenther (2018) but in a condensed form (see Fig. 1).

In the first phase, the management has a leading role to play by determining targets, financial and human resources, responsibilities, and a time schedule for implementation and monitoring activities. The definition of the system's boundaries is decisive for the effort of data collection and stakeholder communication, e.g. when looking at the organizational level (single process, production line, facility, company, or supply chain) at which the MFCA is to be implemented. Following goal and scoping by the organization's management, all relevant quantity centers are to be defined in collaboration with experts from operative business units. A quantity center is a central element of the MFCA model and the virtual representation of a real process or part of it, in which materials are transformed or stored (ISO, 2011).

In the second phase, all relevant input and output flows have to be specified in physical units for each quantity center while respecting the principle of mass conservation. Already at this stage, the organization can benefit from valuable knowledge gain concerning the routes and quantities of production materials, which can contribute to the optimization of operational processes. MFCA differentiates between raw materials, auxiliary materials, and operating materials on the input side and final products, intermediate goods, production losses, emissions, and waste on the output side (see Table 1). When production losses are regarded as costs or efforts and the whole benefit lies with the final product, we are

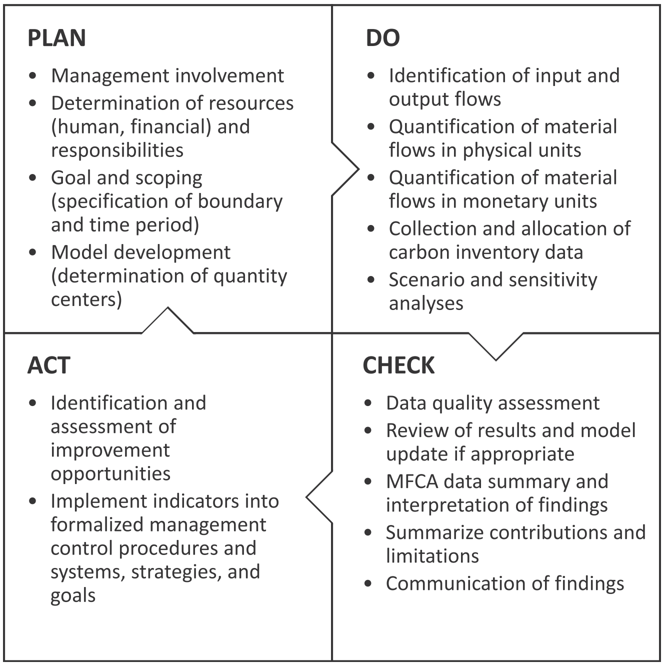

Fig. 1. PDCA cycle for MFCA integrating LCA guidelines, based on ISO (2011) and Rieckhof and Guenther (2018).

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speaking of conventional cost accounting; when production losses are considered as revenues or benefit, we are rather speaking of MFCA (ifu, 2015a; ISO, 2011).

In order to quantify the material flows in monetary units, market prices per item or physical unit have to be researched. Depending on the availability of data, costs are either directly attributed to single quantity centers or indirectly by allocating facility-wide costs to quantity centers following the same allocation rules as for LCA. MFCA discriminates between four cost categories: material costs, system costs, energy costs, and waste management costs. A peculiarity in MFCA is that waste management costs are solely allocated to material losses whereas all other costs can be allocated to products and material losses according to physical, economic, or reasonable user-defined allocation criteria (ISO, 2011). Energy costs can be considered either as direct material costs or separately as variable process costs in the model. System costs comprise non-material direct costs such as depreciation of investments in machinery and equipment, maintenance costs, labor costs, taxes, or other statutory fees. Revenues are generated when products are sold to the market or when resources can be saved by establishing recycling in a closed-loop system, for instance, for process water (Jasch, 2009).

When calculating the carbon footprint, available literature values or life cycle inventory data can be utilized. For complex models, it is advisable to use specialized software tools which also facilitate performing scenario or sensitivity analyses, both being established methods for testing the influence of the value of a single variable on the result.

The third phase serves to review the results and model assumptions, to update input parameter where necessary, to focus on relevant cost flows, and to prepare a meaningful and transparent documentation. Not only does the MFCA have to comply with common quality standards, it must also be suitable for the defined targets. Therefore, a close coordination with the management is required when reviewing and interpreting the results before communicating the results to other stakeholders and deciding on concrete optimization measures in the last phase.

This study investigates cost savings and CO_2 mitigation potentials associated with the introduction of an alternative waste management practice for berry pomace by employing MFCA and carbon footprinting. Schaltegger and Zvezdov (2015) developed a framework for decision situations for MFCA. Pursuant to this, we classify the initial situation and objective of our study as being future and long-term oriented based on an ad-hoc analysis (one-off application of MFCA). We use past information, collected either routinely (energy consumption of existing production line, production volumes, etc.) or ad hoc (equipment for expansion of production line), to support investment decisions by strategic management and to avoid losing added value in the production or, taking a different view, to create added value with a new product.

In the following, all considerations concerning the scope of the analysis and underlying model assumptions are described in detail.

3. Material and methodology

3.1. Goal and scope definition

In order to appraise the proportionate production costs, raw material demand, and global warming potential (GWP) of the berry pomace of a black currant juice production process, an MFCA model was developed with the help of Umberto® NXT MFCA (ifu, 2015b), a special software which emanated from an LCA environment and therefore supports the simultaneous performance of MFCA and carbon footprinting. The carbon footprint was calculated based on life cycle inventory data from ecoinvent 2.2 (result processes and direct emissions) with a time horizon of 100 years (ecoinvent, 2010; IPCC, 2007; Weidema and Hischier, 2010) which accompanied version 7.1.8 of the MFCA software used here. The assessment was carried out in compliance with MFCA ISO standards 14,051/14,052 (ISO, 2011, 2017) and LCA ISO standards (ISO, 2006a, 2006b). Furthermore, the built-in Excel Live-Link function was used to facilitate the definition of input/output places, quantity centers, and parameters.

The development of a model is always associated with two challenges: First, a model should represent a real system as accurately as possible, including all its important elements; second, a model should not be so complex that its behavior and correlations can no longer be understood (Rubinstein and Kroese, 2017). The MFCA model developed here covers the main production steps from the plant cultivation and harvest, through the juice production, and to the end-of-life processing of the berry pomace (cradle-to-grave). For the sake of reducing complexity, certain cost factors which are difficult to quantify, such as maintenance, conveyors, immovable fixed assets (e.g. buildings), clean-in-place system, defrosting of pomace, taxes, resetting of plants, and the cultivation of seedlings, were excluded from the analysis. Moreover, these factors are considered less important for the overall cost balance and environmental impact. The functional unit is defined as *the consumption of clear black currant juice (in liters) produced during one season*.

Investment decisions, such as the extension of a production facility, are usually based on projections about the future state of a company's performance and environment. Scenario analysis, a well-established forecasting technique supporting strategic planning (Brauers and Weber, 1988), was chosen for a comparison of the status quo with a possible alternative waste management practice in the future. From the research questions, literature research, and interviews with experts and practitioners, we first derived two scenarios; a third scenario was added later to explore strategies that could improve the performance:

- The reference or baseline scenario refers to a black currant juice production with a conventional end-of-life of the berry pomace (incineration).
- Alternative scenario I assumes further processing of the berry pomace into a dry powder product (multi-output process).

Table 1
Input and output flows in conventional cost accounting and MFCA based on ISO (2011) and ifu (2015a).

	Costs		Revenue
	Material direct costs	Non-material direct costs (system costs)	
Input	Raw materials, auxiliary material, operating material, energy consumption (energy costs)	Depreciation, energy costs, wages, maintenance, taxes, fees	Production losses (recycled material), unavoidable waste (e.g. process water), emissions (carbon capture, carbon credits)
Output	Intermediate goods, production losses, unavoidable waste, wastewater, emissions (waste management costs)		Final product

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- Alternative scenario II considers the processing of berry pomace and additional apple pomace to optimize the overall cost balance (multi-output process).

3.2. General model assumptions

For the general technical configuration of the juice production line and basic economic issues, data from a regional producer in Germany with a diverse product portfolio (apples, citrus fruits, multivitamin, and berries) was used, which is in terms of size and business model a typical representative of the industry. We assumed a new acquisition of the entire production line in our model. In the case that only purchase prices for used equipment could be researched and no information on the production date is available, a conservative approach was taken and the original equipment net price was recalculated by assuming a minimum age of five years and a residual value of 20%. Further input data was derived from literature values, market data, or estimated values based on expert knowledge. Using proxies in this way is common practice and uncritical as long as it is adequately documented (METI, 2007).

In the following, key input parameters for the model are described and, in addition, listed in Table 2. In addition, all input data used in the model are listed in Table S.1 (supplementary material) along the production process to facilitate traceability of their use and origin.

In the case of the regional juice producer considered here, with a total raw material production of 8000 t per year, including apples and other fruits, 250 t (217.5 t including a 13% harvest loss) can be attributed directly to black currants. This corresponds to an average yield of 6.19 t/ha and a cultivated area of 40.4 ha (see Table 2). With a production capacity of 5 t/h, it would take 43.5 h to process the entire harvest. The relative density of pure BC juice (100% fruit content) amounts to 1.042 (Rehlender, 2016). For the purpose of simplification and unit consistency, a density of 1000 g/L for raw and clear BC juice was assumed and all mass flows in the model were defined in kg. The bulk density of fresh BC pomace before milling was measured to be 393 g/L and decreased to 319 g/L after milling and drying (TU Dresden, 2017). Losses in the juice production process such as heat losses or unprecise filling are neglected as they could not be quantified in this study.

Juice production lines are complex technical systems and usually individually tailored to the requirements of the juice producer, e.g. depending on the raw materials being processed. In the absence of an engineering plant simulation that quantifies the energy consumption of individual pieces of equipment and production steps and distinguishes between different input materials, not all energy-consuming processes could be adequately replicated in the MFCA model. Therefore, aggregated energy consumption figures that are provided on the facility level for the period 2010–2012 were allocated to the black currant juice production in 2015 based on physical mass flows (BC ratio of 2.72%). In a first attempt, the energy consumption of individual machines was calculated based on technical data sheets or product descriptions to derive appropriate criteria for further allocating the energy costs to quantity centers. It turned out that about 60% of the theoretical electricity consumption of 17,649 kWh could not be directly explained by the production processes considered in the model. Other criteria such as machine hours, production volume, or number of employees (ISO, 2011) also failed to serve as suitable allocation criteria. For this reason, the theoretical electricity consumption of 17,649 kWh was equally allocated to the eight major production steps (crushing, mashing, pressing/separation, short-term heating, storage, filtration, mixing, pasteurization/bottling) and the theoretical process heat consumption of 61,903 kWh was equally attributed to the three main heat-demanding processes (mashing, short-term heating, pasteurization/bottling). Energy prices for electricity (€0.16/kWh) and natural gas (€0.05/kWh) refer to the year 2011, but had not changed significantly by 2015/16 (Anonymous, 2016). The fuel price in 2016 (€1.29/kg) was taken from a literature source (statista, 2018).

For most tangible assets, a linear depreciation between 8 and 12 years for costs and physical masses was assumed throughout the study (e.g. 8 years for metal barrels, 9 years for trucks, 10 years for filling lines, and 12 years for tractors and harvesters). Black currant bushes have a lifetime of up to 12 years (Anonymous, 2016; Duponcel, 2007). However, their productivity is not constant every season, but is instead normally distributed over the whole lifetime. In order to take account of the natural variability at different locations in Germany and at the same time establish a practicable framework for modeling, a depreciation period of 12 years was defined. A single glass bottle can be refilled between 40 and 50 times (Umweltbundesamt, 2018; VdF, 2018) before it becomes too

Table 2
Key input parameters for the model.

Parameter	Value	Unit	Source
Total production	8000	t/a	gross mass including apples (Anonymous, 2016)
BC total harvest yield	250	t/a	Anonymous (2016)
BC yield after harvest	217.5	t/a	13% lost (Anonymous, 2016)
BC yield per hectare	6.19	t/ha	average yield in Germany in 2015 (Anonymous, 2016)
BC area cultivated	40.39	ha	calculated, total yield/yield per hectare
Ratio of BC	2.72	%	calculated, yield after harvest/total production
BC production capacity	5	t/h	Anonymous (2016)
BC production duration	43.5	h	calculated, yield after harvest/production capacity
Density of raw and clear BC juice	1000	g/L	simplifying assumption based of the relative density of pure BC juice (1.042) reported by Rehlender (2016)
Bulk density of pomace before milling	393	g/L	TU Dresden (2017)
Bulk density of pomace after milling	319	g/L	TU Dresden (2017)
BC electricity consumption	17,649	kWh/a	mean value 2010–2011, BC allocated (Anonymous, 2012)
BC process heat consumption	61,903	kWh/a	natural gas for process heat (steam, hot water), mean value 2010–2012, BC allocated (Anonymous, 2013)
Electricity price	0.16	€/kWh	price 2011 (Anonymous, 2012)
Natural gas price	0.05	€/kWh	price 2011 (Anonymous, 2012)
Fuel price (diesel)	1.29	€/kg	2016: €1.08/L rounded up (statista, 2018), density 0.84 kg/L (DIN, 2017)
Depreciation	8–12	a	based on BMF (2000) and expert opinion
Lifetime of a 1L-bottle	40	fillings	conservative assumption based on Umweltbundesamt (2018) and VdF (2018)
Wages, hourly, Germany	11.00	€/h	Anonymous (2016)

BC: black currant.
All prices are given as net prices excluding value added tax (VAT).

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damaged by scratches caused during cleaning and transportation (first loop). Another beneficial feature of a glass bottle is that it can be fully recycled at the end-of-life (second loop) (Deutsche Umwelthilfe, 2014). As a conservative approach, we assume a life time of 40 filling cycles in the model; however, the cleaning and secondary recycling of BC juice bottles was neglected in this case study because of the low share in total juice production. As the MFCA model was designed for one period only, discount rates and price developments were not considered here. Labor costs are gross figures and were calculated at €11.00/h based on the €8.50/h statutory minimum wage (reference year 2016) and including the employer's social contribution.

In case that CO_2 inventory data for a particular substance was missing in ecoinvent, data from the most similar substance was used (e.g. *polyacrylonitrile (PAN)* was chosen as the membrane material instead of *styrene acrylonitrile (SAN)*). When the exact technical equipment was not included in ecoinvent, the carbon footprint of the preceding intermediate product or raw material was used. Since almost everything is made of stainless steel in the beverage production, the ecoinvent result process *steel product manufacturing* was primarily applied as a proxy for steel equipment. In cases where the actual weight of a production machine or equipment deviates from the corresponding ecoinvent result process, a linear correction factor was used (linear scaling to exact weight) to avoid an under- or overestimation of the carbon dioxide emissions. Where data from the referenced literature did not match the true capacity of the machine or equipment, the given values for weight, power output, or price were linearly scaled to a production capacity of 5 t/h to calculate CO_2 emissions and purchase costs more accurately.

At the end of life, carbon credits were awarded by system expansion for the incineration of pomace as biowaste (in reference and alternative scenarios) and for the partial substitution of sugar, fat, and flour in cakes (alternative scenarios). Morandé et al. (2017) found a 15-year-old Californian vineyard to capture and store 12.3 t carbon per ha. As such figures are missing for BC plants, their yearly carbon fixation was neglected in the model. All emission factors used in the study for input and output flows are listed in Table 3.

3.3. *Cost categories*

All costs related to the material and energy flows in the MFCA model were assigned to the four different cost categories as defined in ISO (2011) (see Table 4). The same categorization and coloring applies to the full list of input parameters provided in Table S.1. For the sake of completion, further project materials such as intermediate goods, losses, and final products, which have to be specified in Umberto® NXT MFCA to set up the model, are also presented here. Energy costs were included as direct material costs in order to connect them with the corresponding CO_2 inventory dataset. Waste management costs relate to the transport of pomace to the municipal waste incineration plant including the proportional depreciation of the truck and expenses for fuel and labor. Final energetic recovery in the waste incineration plant is charged at only €15.00/t for non-compostable organic waste (Anonymous, 2016) as, in the present case, all transport costs are borne by the juice producer.

3.4. *Final model*

The material and cost flows (arrows) and quantity centers (squares) throughout all life cycle phases of a black currant juice production are presented in Fig. 2. The cultivation and processing of berries results in material losses and causes separation into different material fractions (liquid, solid). Since the waste-related costs are of great interest in MFCA and, particularly in the cases of the alternative scenarios, a separation of the now joint production process is not possible, allocations could not be avoided as recommended for life cycle assessments (Buxmann et al., 1998; ISO, 2006b). In the case of berry juice production, physical allocation was regarded as being the best criterion for allocating costs fairly to products and material losses in four quantity centers (harvest, pressing/separation, filtration, and milling/drying). Moreover, it was decided to relieve water evaporated during the milling and drying of berry pomace in the alternative end-of-life (EoL) scenarios from all costs. Finally, the model requires the definition of a reference flow which was set at 530,632.42 kg of final juice product

Table 3
Emission factors.

Flow	Dataset	Emission factor	Unit	Source
Fertilizer	Potassium nitrate, as N, at regional storehouse [RER]	15.98	kg CO_2eq/kg	ecoinvent 2.2
Enzyme	Literature value for pectinase	5.31	kg CO_2eq/kg	Alexiades et al. (2018)
Water	Tap water at user [RER]	3.19E-04	kg CO_2eq/kg	ecoinvent 2.2
Sugar	Sugar from sugarbeet at sugar refinery [CH]	0.51	kg CO_2eq/kg	ecoinvent 2.2
Tractor	Tractor, production [CH], 3 t, 7000 h	6.13	kg CO_2eq/kg	ecoinvent 2.2
Vibrating machine	Harvester, production [CH], 10 t, 1300 h	4.58	kg CO_2eq/kg	ecoinvent 2.2
Truck	Lorry 16 t [RER]	19,190.0	kg CO_2eq/unit	ecoinvent 2.2
Tubular heat exchanger	Heat exchanger of min CHP plant [CH]	89.37	kg CO_2eq/unit	ecoinvent 2.2
Electrical pump	Pump 40W at plant [CH], based on Grundfos UP 15–35 × 20, 2.5 kg (Grundfos, 2018)	7.04	kg CO_2eq/unit	ecoinvent 2.2
Membrane	Styrene-acrylonitrile copolymer, SAN, at plant [RER]	4.06	kg CO_2eq/kg	ecoinvent 2.2
Other steel equipment	Steel product manufacturing, average metal working [RER]	1.8	kg CO_2eq/kg	ecoinvent 2.2
Transport boxes	Polyethylene, HDPE, granulate, at plant [RER]	1.95	kg CO_2eq/kg	ecoinvent 2.2
Plastic bags	Nylon 6, at plant [RER]	9.28	kg CO_2eq/kg	ecoinvent 2.2
Bottles	Packaging glass, white, at plant [DE]	0.62	kg CO_2eq/kg	ecoinvent 2.2
Caps	Aluminum product manufacturing, average metal working [RER]	3.37	kg CO_2eq/kg	ecoinvent 2.2
Labels	Paper, woodfree, coated, at non-integrated mill [RER]	1.17	kg CO_2eq/kg	ecoinvent 2.2
Fuel	Diesel, low-sulphur, at regional storage [CH]	0.61	kg CO_2eq/kg	ecoinvent 2.2
Electricity	Electricity, low voltage, at grid [DE]	0.72	kg CO_2eq/kWh	ecoinvent 2.2
Process heat	Heat, natural gas, at boiler atmospheric non-modulating <100 kW [RER]	0.28	kg CO_2eq/kWh	ecoinvent 2.2
Residues	disposal, biowaste, 60% H2O, to municipal incineration, allocation price [CH]	0.03	kg CO_2eq/kg	ecoinvent 2.2
Electricity credit	electricity mix [DE]	0.64	kg CO_2eq/kWh	ecoinvent 2.2
Heat credit	heat, at cogen 1MWe lean burn, allocation energy [RER]	0.09	kg CO_2eq/MJ	ecoinvent 2.2
Sugar credit	Literature value for sugar	0.6	kg CO_2eq/kg	ifeu (2018)
Flour credit	Literature value for wheat flour	0.34	kg CO_2eq/kg	ifeu (2018)
Fat credit	Literature value for butter	9.2	kg CO_2eq/kg	ifeu (2018)

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Table 4
Cost categories and project materials applied in the MFCA model.

Cost category	Sub category	Item
Material costs	Raw, auxiliary, and operating materials	Plants, fertilizer, pectinase, water, sugar, bottles, caps, labels, plastic bags
Energy costs	Energy	Fuel, electricity, process heat (natural gas)
System costs	Depreciation	Production machines and equipment (vehicles, transport boxes, filtration equipment, tanks, etc.)
	Labor costs	Wages
Waste management costs	Waste management	Waste transport, waste disposal fee
Further project materials	Intermediate goods	Currants, juice, pomace (raw, cooled, crushed, mashed, milled etc.)
	Products	Final juice, final processed pomace
	Losses, production waste, unavoidable waste	Currants lost during harvest, press cake and suspended matter (reference scenario), fertilizer leached, water evaporated
	Emissions	Carbon dioxide, credits from incineration of pomace (cogeneration of heat and electricity), credits from substitution of sugar, fat, and flour in cake

(corresponding to 520,483 1L-bottles) in the quantity center *bottling*. In Table S.1, the concrete input and output variables are given for each quantity center together with an explanation of underlying assumptions and references.

4. Results and discussion

4.1. MFCA results

Within Umberto® NXT MFCA, the calculation of the model runs backwards from the reference flow to the first quantity center. All costs or CO_2 emissions are passed on to the next quantity center and summed up. Following the calculation of the total flows, the results can be exported in a detailed form (per quantity center) or in an aggregated form as a costs/GWP matrix overview. Table 5 shows the aggregated MFCA results for all main cost categories, subdivided into product- and waste-related costs.

In the baseline scenario, the overall share of material costs is basically high at 63%, followed by system costs at 27%, energy costs at 9%, and waste management costs at roughly 1%, whereas in the alternative scenario system costs can account for up to 44%. The share of material losses in the baseline scenario lies at 19.2% which is significant but technologically justified (efficiency of mechanical harvesting, separation and filtration processes) and bears only limited optimization potential. It therefore seems more interesting to optimize the overall cost balance through the creation of a second marketable product from the pomace. Our analysis showed a reduced share of 4–5% in such a multi-product process. However, under the given model assumptions and selling prices (€1.00/L juice, €0.50/kg pomace), there is a deficit of approximately €27,700 against the baseline scenario due to higher investment and energy costs for cooled storage of the pomace. Even if the milling/drying machine is better utilized over the year by processing apple pomace and the pomace revenue increases, this deficit remains. We assumed an intelligent cooling concept where the same equipment is used consecutively over 171 days (98 days without apple pomace) to keep the investment costs for pomace processing constant, but energy costs rose and ate up the revenue. Nevertheless, potential energy savings are conceivable by relying on other cooling concepts or direct drying measures which might also be cheaper but have not been investigated in this study and, therefore, opens doors for future research.

Figs. 3 and 4 show all life cycle phases and processes considered in the MFCA model and where the main cost drivers are located. In terms of material costs and system costs, the plant cultivation and harvesting phase is particularly relevant due to high costs for BC plants, special harvesting equipment, and labor costs. These single cost factors are summarized in the cost driver *BC production*, which is given consideration later in the uncertainty analysis. Another relevant cost driver concerns the material costs for the packaging of the final juice. We decided to examine the influence of this cost driver on the final result in the uncertainty analysis together with ideas on how to optimize the chosen cooling concept of pomace in the alternative scenarios. The visual cost overview for alternative scenario II does not deviate significantly from that of alternative scenario I and is therefore not presented here.

4.2. Carbon footprint results

The total global warming potential of 520,483 1-L bottles of European black currant juice, the final product in the baseline scenario, amounts to 64.2 t CO_2eq (see Table 6). This corresponds to 0.12 kg CO_2eq/L, a value that lies between Florida orange juice with 0.19–0.23 kg CO_2eq/L (Spreen et al., 2010) and Malaysia fruit juice with 0.07 kg CO_2eq/L (Rahim and Raman, 2015). Better reference values, i.e. specifically for BC juice purchased in glass bottles, were not available at the time of writing the study. The value for the baseline scenario includes carbon credits of −3.36 t CO_2eq from the incineration of pomace. Much higher carbon credits between −92.3 (alternative I) and −184.6 t CO_2eq (alternative II) are obtained from the replacement of sugar, flour, and fat in cakes. This leads to a GWP of 0.05 kg CO_2eq/L and −0.07 kg CO_2eq/L, respectively. The valorization of the by-product berry pomace can therefore improve the ecological performance of the main product berry juice, at least on the balance sheet and disregarding possible rebound effects.

4.3. Uncertainty analysis

Uncertainty analysis within LCA is a “systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability” (ISO, 2006a: 12). According to Huijbregts (1998), uncertainty in LCA includes parameter uncertainty, model uncertainty, and uncertainty due to choices, whereas variability relates to real world variations, such as spatial variability or temporal variability. As this issue is not

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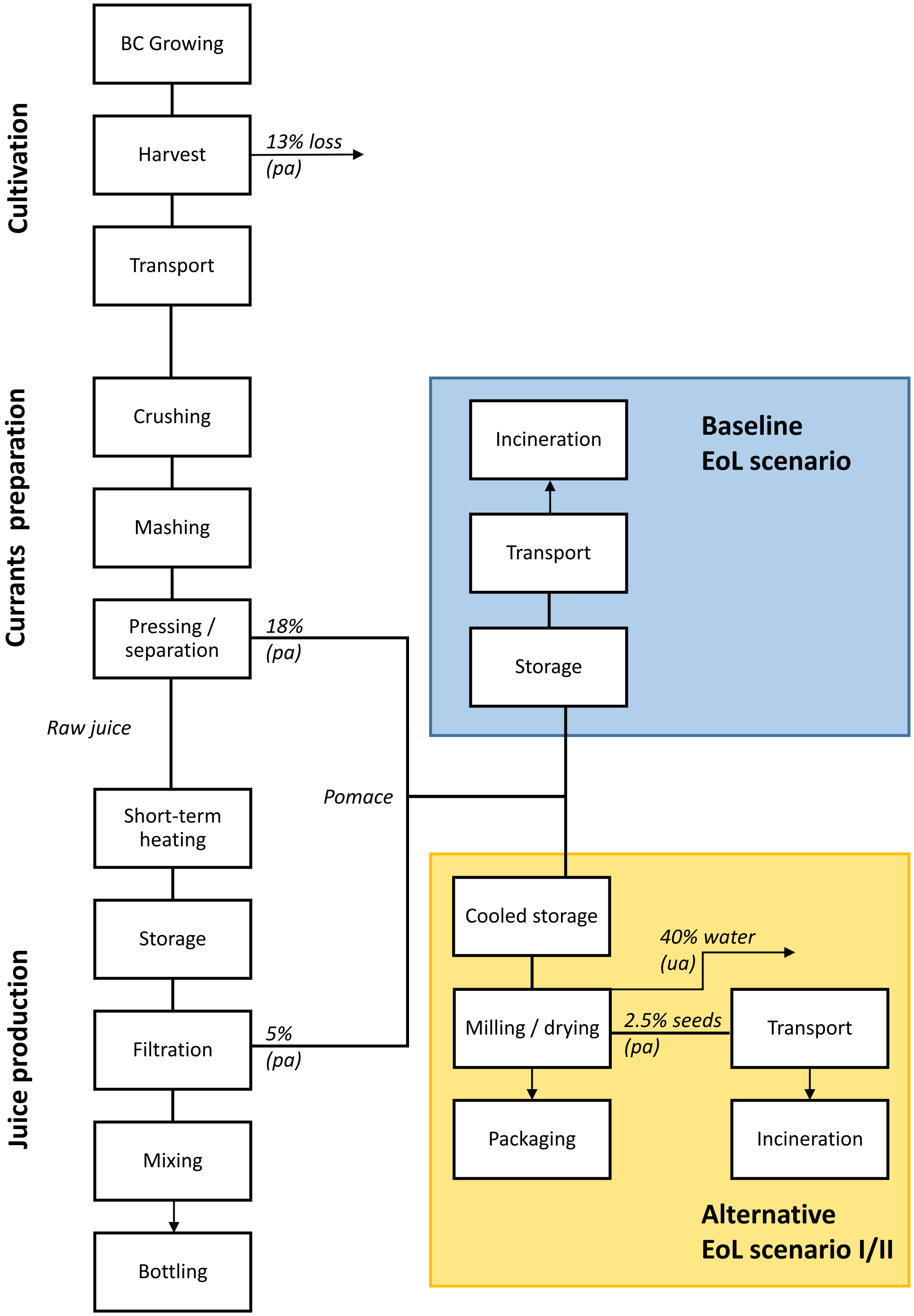

Fig. 2. MFCA model including all life cycle phases, three end-of-life (EoL) scenarios for berry pomace, and inevitable allocations of quantity center costs (pa: physical allocation; ua: user-defined allocation).

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Table 5
Costs matrix overview for baseline and alternative scenarios.

Scenario	Category	Products (€)	Material losses (€)	Total costs (€)	Share of material losses
Baseline	Material costs	49,513.60	9507.15	59,020.75	10.2%
	Energy costs	6839.10	1216.85	8055.95	1.3%
	System costs	19,070.95	5909.64	24,980.59	6.3%
	Waste management costs	0.00	1279.32	1279.32	1.4%
	Total costs	75,423.65	17,912.96	93,336.61	**19.2%**
	Revenue	520,483.00	0.00	520,483.00	
	Profit			**427,146.39**	
Alternative I	Material costs	56,323.31	3574.05	59,897.36	2.7%
	Energy costs	15,752.97	322.24	16,075.21	0.2%
	System costs	56,412.58	2282.46	58,695.04	1.7%
	Waste management costs	0.00	159.38	159.38	0.1%
	Total costs	128,488.87	6338.12	134,826.98	**4.7%**
	Revenue	520,483.00	13,820.00	534,303.00	
	Profit			**399,476.02**	
Alternative II	Material costs	57,201.39	3572.88	60,774.28	2.4%
	Energy costs	22,361.58	388.90	22,750.47	0.3%
	System costs	62,269.37	2332.67	64,602.04	1.6%
	Waste management costs	0.00	177.37	177.37	0.1%
	Total costs	141,832.34	6471.82	148,304.15	**4.4%**
	Revenue	520,483.00	27,645.00	548,128.00	
	Profit			**399,823.85**	

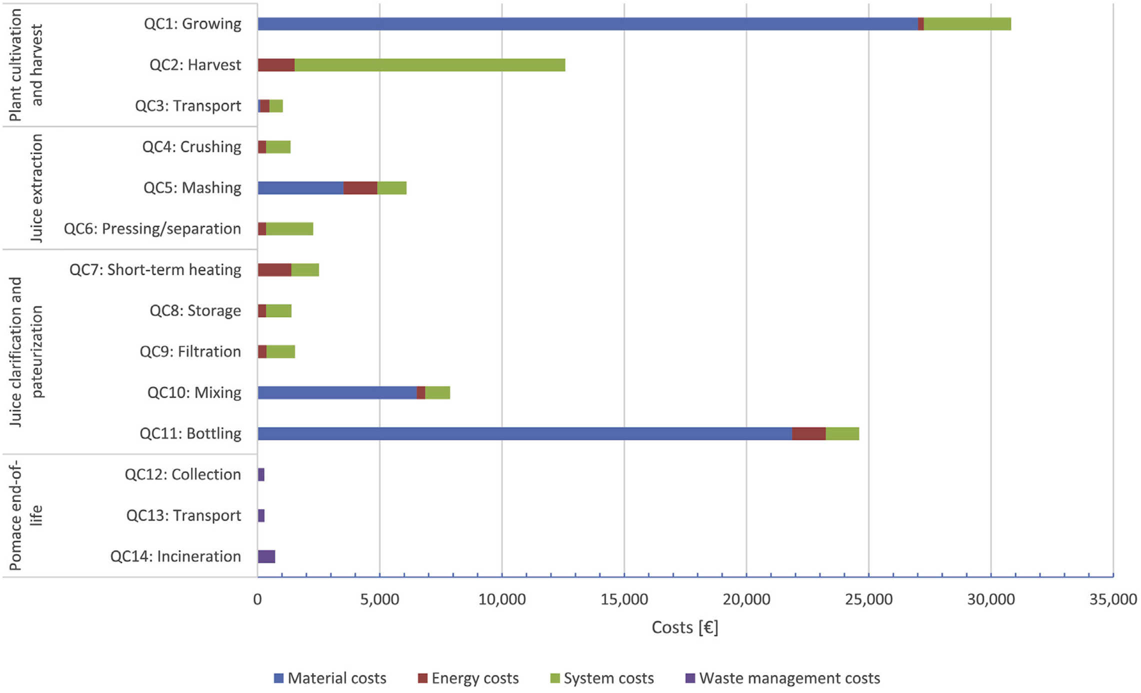

Fig. 3. Cost overview according to life cycle phases and processes (Baseline scenario).

described in the MFCA ISO standards, we refer here to the uncertainty classification for LCA. Huijbregts (1998) further states that parameter uncertainty can be addressed by performing stochastic modeling or expert judgements. Uncertainty due to choices when developing the model can be counteracted by standardization, scenario analysis, or peer review. In the following sections, we use the term *uncertainty* as umbrella term for uncertainty and variability aspects. Model uncertainty caused by simplifications such as linear modeling of environmental processes are not covered by the uncertainty analysis applied in this study.

4.3.1. Parameter uncertainty

With the study presented here, we concur with Gale (2006) that MFCA data is not always extractable from existing inventories. The acquisition of investment costs proved to be the most problematic due to the individually tailored production line and missing up-to-date supply chain data. Where possible, we tried to recalculate original prices. Worst-case assumptions are used if data gaps or unrepresentative data appear. However, an accurate mapping of all equipment costs would require a systematic inventory of an existing production line, which was impossible in most parts of the study due to data confidentiality concerns. Moreover, we used an early version of Umberto NXT MFCA from 2015 which included only an outdated inventory database; meanwhile, ecoinvent 3.5 has been made available. The results for the carbon footprint, therefore, may slightly deviate from an analysis with more recent figures.

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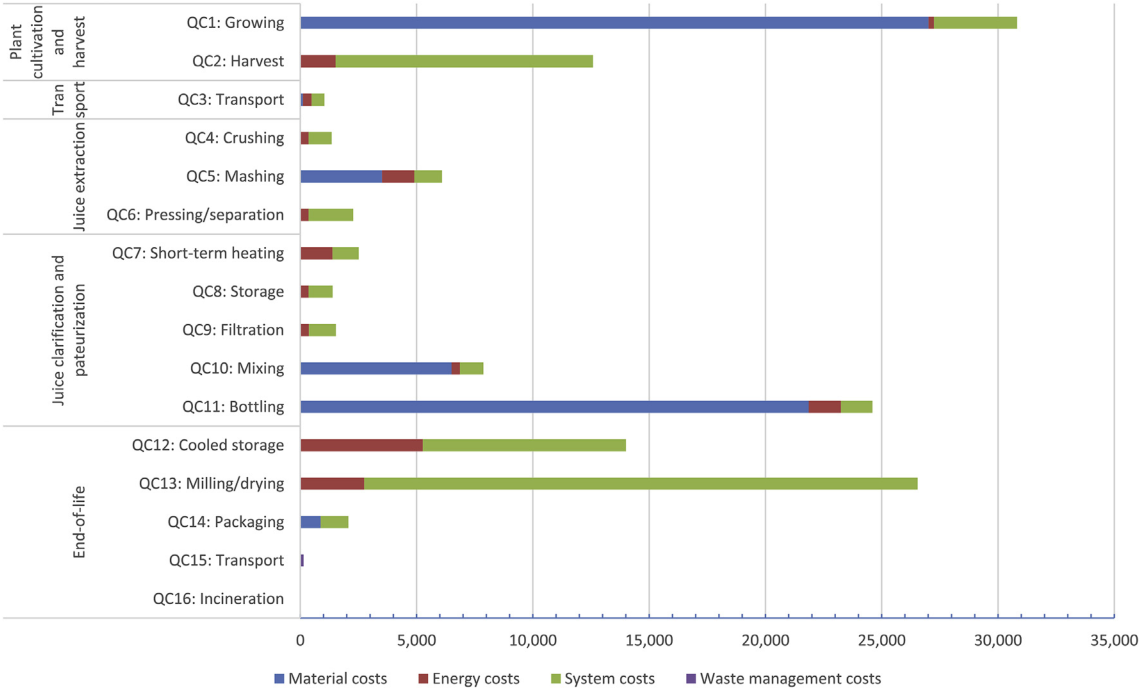


Fig. 4. Cost overview according to life cycle phases and processes (Alternative scenario I).

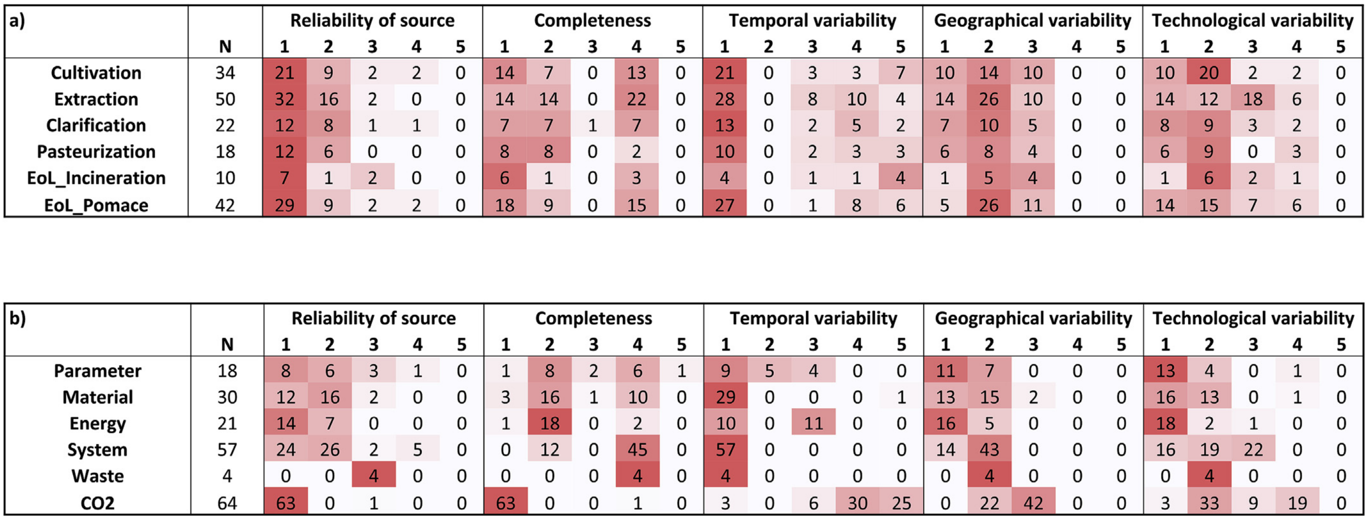
Table 6
GWP matrix overview for baseline and alternative scenarios.

Scenario	Category	Products (kg CO_2eq)	Material losses (kg CO_2eq)	Total GWP (kg CO_2eq)
Baseline	Material GWP	25,282.69	4315.20	29,597.89
	Energy GWP	27,767.96	−161.97	27,605.99
	System GWP	3635.85	1822.18	5458.03
	Waste management GWP	0.00	1494.24	1494.24
	Total GWP	56,686.50	7469.65	**64,156.15**
Alternative I	Material GWP	−56,753.86	9227.02	−47,526.84
	Energy GWP	50,904.32	17,142.35	68,046.67
	System GWP	4228.79	1043.73	5272.53
	Waste management GWP	0.00	37.58	37.58
	Total GWP	−1620.74	27,450.67	**25,829.94**
	Juice GWP			58,525.10
	Pomace GWP			−32,695.17
Alternative II	Material GWP	−141,703.79	1879.32	−139,824.48
	Energy GWP	98,437.18	679.27	99,116.45
	System GWP	4656.77	615.75	5272.53
	Waste management GWP	0.00	74.84	74.84
	Total GWP	−38,609.84	3249.18	**−35,360.66**
	Juice GWP			58,525.10
	Pomace GWP			−93,885.76

Owing to the multitude of model parameters, some of which had to be estimated, the pedigree matrix from Weidema and Wesnaes (1996) was applied in this study. It is a well-established approach used in LCA to identify data quality aspects that may influence the reliability of study results and thus their robustness for decision making (Guo and Murphy, 2012). For instance, ecoinvent 2 applies the pedigree matrix in the form of a data quality matrix with a numerical scoring of 1–5 in order to estimate the uncertainty of flow data (Frischknecht and Rebitzer, 2005). Ciroth et al. (2016) later refined this approach by introducing empirically based uncertainty factors as alternative to qualitative expert judgements.

Input data are usually subject to a systematic uncertainty through measurement errors (basic uncertainty) and additional uncertainty related to insufficient quality aspects (reliability, completeness, temporal correlation, geographical correlation, further technological correlation) (Weidema and Wesnaes, 1996). Since the basic uncertainty of all physical and monetary parameters used in the model is unknown to us, we concentrate in the following on the additional uncertainty only.

The final pedigree matrix as depicted in Fig. 5 is structured into the main data quality indicators with five score values (columns) and further specified by life cycle phases and parameter categories (rows). Aggregation of the semi-quantitative scores can be misleading and should be avoided (Weidema and Wesnaes, 1996). In Fig. 5, however, scores of 194 input variables were summed up to easier detect hot spots of data quality issues. Reliability, i.e. how the data was obtained, is overall satisfying over all life cycle phases and parameter categories. Completeness, the second indicator to describe the representativeness of data, is partly limited, especially



a)		Reliability of source					Completeness					Temporal variability					Geographical variability					Technological variability				
	N	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Cultivation	34	21	9	2	2	0	14	7	0	13	0	21	0	3	3	7	10	14	10	0	0	10	20	2	2	0
Extraction	50	32	16	2	0	0	14	14	0	22	0	28	0	8	10	4	14	26	10	0	0	14	12	18	6	0
Clarification	22	12	8	1	1	0	7	7	1	7	0	13	0	2	5	2	7	10	5	0	0	8	9	3	2	0
Pasteurization	18	12	6	0	0	0	8	8	0	2	0	10	0	2	3	3	6	8	4	0	0	6	9	0	3	0
EoL_Incineration	10	7	1	2	0	0	6	1	0	3	0	4	0	1	1	4	1	5	4	0	0	1	6	2	1	0
EoL_Pomace	42	29	9	2	2	0	18	9	0	15	0	27	0	1	8	6	5	26	11	0	0	14	15	7	6	0

b)		Reliability of source					Completeness					Temporal variability					Geographical variability					Technological variability				
	N	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Parameter	18	8	6	3	1	0	1	8	2	6	1	9	5	4	0	0	11	7	0	0	0	13	4	0	1	0
Material	30	12	16	2	0	0	3	16	1	10	0	29	0	0	0	1	13	15	2	0	0	16	13	0	1	0
Energy	21	14	7	0	0	0	1	18	0	2	0	10	0	11	0	0	16	5	0	0	0	18	2	1	0	0
System	57	24	26	2	5	0	0	12	0	45	0	57	0	0	0	0	14	43	0	0	0	16	19	22	0	0
Waste	4	0	0	4	0	0	0	0	0	4	0	4	0	0	0	0	0	4	0	0	0	0	4	0	0	0
CO2	64	63	0	1	0	0	63	0	0	1	0	3	0	6	30	25	0	22	42	0	0	3	33	9	19	0

Fig. 5. Pedigree matrix sorted by a) life cycle phases and b) parameter categories.

for system costs, as data is often based on one sample and period only. For the majority of input variables an adequate temporal correlation could be achieved, except for carbon inventory data as previously argued. Geographical variability can be described as sufficient considering that most of the data applies to German or at least European conditions. The technological variability indicates the compromises that had to be made because technology-specific costs and emission factors were partly unavailable and surrogates had to be used instead.

4.3.2. *Scenario uncertainty*

Apart from parameter uncertainty, uncertainty stemming from the scenario development, goal and scope definitions, model simplifications, and biased estimations can also be critical for the credibility of the outcomes of life cycle analyses and thus for private and public decision making (Lloyd and Ries, 2007). Gregory et al. (2013) defined probability distributions for key model parameters as part of a probabilistic scenario analysis in order to evaluate the differences in the GWP of different hand drying systems. In doing so, they integrated parameter uncertainty analysis into traditional scenario uncertainty analysis. We followed a similar approach for our MFCA model and investigated the sensitivity of changes in monetary input data, energy and mass flows on the net profit results of the baseline and alternative scenarios with the help of a Monte Carlo simulation using the spreadsheet-based risk analysis tool Crystal Ball (Oracle, 2019). A Monte Carlo simulation is a numerical stochastic approach to describe and anticipate complex phenomena by generating a sequence of (pseudo)random numbers which are drawn from distribution functions with the help of computational algorithms (Kalos and Whitlock, 1986). Such random samplings can serve to examine the stochastic uncertainty of model input data and their influence on the accuracy of the MFCA results. However, the numerical solution obtained can only be an approximation of the behavior of real-life systems (Rubinstein and Kroese, 2017).

A set of 18 monetary input variables was selected based on previous findings, which comprises variables with higher uncertainty due to poor representativeness, high cost intensity, or spatial variability (see Table 7, original input variables used in the three scenarios are written in bold and further manifestations of these input variables in standard type). The current MFCA model assumes that BC plants are grown by the juice producer in self-cultivation at costs of €0.18/kg, which seems to be somewhat underrated. To ensure better transferability of results to situations where berries are purchased from other producers, e.g. in the absence of their own farmland or severe harvest failure, a *BC production price* of €1.00/kg was considered as most likely when compared to €0.28/kg for Polish black currants and €2.29/kg for German black currants (Tridge, 2019). Because the customers' sense of taste can differ due to regional, cultural, or lifestyle-related grounds, *water-juice ratio* and *sugar added* were chosen for the uncertainty analysis as they have a large influence on the energy value, taste, and viscosity of the juice. Pursuant to the Fruchtsaft-und Erfrischungsgetränkeverordnung – FrSaftErfrischGetrV (BMJV, 2004), the fruit content of BC juice (more precisely BC nectar) must have a minimum of 25%, which corresponds to a maximum allowed *water-juice ratio* of 3:1. The MFCA identified the freezing and further processing of the pomace as an important cost factor so that the sensitivity of equipment and energy costs was of great interest to the authors. Finally, it is anticipated that the selling prices for juice and pomace will be important levers for optimizing the cost balance. For example, organic quality can justify a 30% higher selling price for BC juice (Anonymous, 2016). An attractive selling price for BC pomace mainly depends on the targeted clientele and their acceptance of possibly changed product properties. BC pomace intended to be used as an additive in pharmaceutical products and cosmetics, or as a sports nutrition supplement, can lead to higher revenues than as an additive in basic foods. The price range of frozen berry pomace can vary between €0.50 and €9.00/kg, as stated in interviews with producers in Sweden and Poland (Brunneby, 2017; Frunutex, 2017).

Most of the input variables selected can be considered as independent from each other. A correlation of −0.7 (strong) was assumed between *BC production price* and *total harvest yield* since it is assumed that the lower the own harvest yield, the higher the costs for the additional purchase of BC. Another correlation of −0.5 (moderate) was assumed between *price milling/drying machine* and *thermal/electric capacity* as the manufacturer foresees energy savings of −20%/kg input for a machine of larger scale (Görgens, 2019). Probability distributions used here (see Table 7) were selected according to the available data and assumed likelihood of occurrence of the respective phenomenon, and are regarded to approximate the real world with sufficient accuracy. The authors decided to run

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Table 7
Original and potential input variables for Monte Carlo simulation and contribution to variance.

Uncertain assumption	Input			Contribution to variance		
	Probability distribution	Parameter	Rationale	Baseline	Alternative I	Alternative II
Total process heat	Uniform	Min 46,424 kWh/a, **Max 61,903 kWh/a**	−25% savings (Anonymous, 2013)	0.0%	0.0%	0.0%
Total electricity	Triangular	Min 16,806 kWh/a, Max 18,492 kWh/a, **Most likely 17,649 kWh/a**	Min and Max measured values for 2010 and 2011, Most likely mean value (Anonymous, 2012)	0.0%	0.0%	0.0%
Total harvest yield[1]	BetaPert	Min 0 t/a, Max 300 t/a, **Most likely 250 t/a**	Min and Max estimated, Most likely value (Anonymous, 2016)	0.3%	0.0%	0.1%
Wage hourly	Triangular	Min €10.10/h, Max €12.63/h, **Most likely €11.00/h**	Min (BMJV, 2014)[2], Max (BMAS, 2018), Most likely (Anonymous, 2016)	0.0%	0.0%	0.0%
BC production price[1]	Triangular	Min €0.18/kg, Max €2.29/kg, **Most likely €1.00/kg**	Min own model, Max (Tridge, 2019), Most likely estimated	−27.9%	−16.0%	−7.3%
Price pectinase	Triangular	Min €45.98/L, Max €68.96/L, **Most likely €53.90/L**	Min and Max estimated, Most likely (Bockmeyer, 2017)	0.0%	0.0%	0.0%
Price centrifuge	Triangular	Min €120,000, Max €280,000, **Most likely €200,000**	Anonymous (2016)	0.0%	0.0%	0.0%
Water-juice ratio	Discrete/ user-defined	**x1 (2:1) = 338,966.66 kg water**, p1 = 80%, x2 (3:1) = 508,449.99 kg water, p2 = 20%	Changed viscosity for different sense of taste	47.0%	33.7%	18.7%
Sugar added	Discrete/ user-defined	**x1 (7.1g/100g) = 12,033.32 kg sugar**, p1 = 80%, x2 (5.3g/100g) = 8982.62 kg sugar, p2 = 20%	−25% savings estimated	0.1%	0.0%	0.0%
Bottles reuse cycle	Triangular	Min 30x, Max 50x, **Most likely 40x**	Estimated based on ifeu (2010) and VdF (2018)	0.0%	0.0%	0.0%
Selling price juice	Uniform	**Min €1.00/bottle**, Max €1.30/bottle	Min conventional quality, Max organic quality (Anonymous, 2016)	24.5%	14.9%	6.2%
Depreciation metal barrels	Discrete/ user-defined	**x1 (8a) = €4060.45**, p1 = 50%, x2 (1a) = €32,483.60, p2 = 50%	Estimated based on Haufe (2018)		1.5%	0.6%
Price refrigeration container	Discrete/ user-defined	**x1 (new) = €22,000**, p1 = 50%, x2 (used 5a, −80%) = €4,400, p2 = 50%	Estimated based on MT Container (2019a)		0.0%	0.0%
Refrigeration container electric capacity	Triangular	Min 6 kW, Max 10 kW, **Most likely 7 kW**	Estimated based on MT Container (2019b)		0.0%	0.0%
Price milling/drying machine[3]	Discrete/ user-defined	**x1 (new) = €185,000**, p1 = 60%, x2 (used 5a, −80%) = €37,000, p2 = 20%, x3 (upscaled size +20%) = €222,000, p3 = 20%	Depreciation estimated based on Görgens (2019)		0.2%	0.1%
Milling/drying machine thermal capacity[3] (Alternative I)	Discrete/ user-defined	**x1 (44 kWh/100 kg) = 21,156.04 kWh**, p1 = 80%, x2 (larger size, −20%/kg input, 35.20 kWh/100 kg) = 16,924.84 kWh, p2 = 20%	Estimated based on Görgens (2019)		0.1%	
Milling/drying machine electric capacity[3] (Alternative I)	Discrete/ user-defined	**x1 (22 kWh/100 kg) = 10,578.02 kWh**, p1 = 80%, x2 (larger size, −20%/kg input, 17.6 kWh/100 kg) = 8462.42 kWh, p2 = 20%	Estimated based on Görgens (2019)		0.0%	
Milling/drying machine thermal capacity[3] (Alternative II)	Discrete/ user-defined	**x1 (44 kWh/100 kg) = 42,312.09 kWh**, p1 = 80%, x2 (larger size, −20%/kg input, 35.20 kWh/100 kg) = 33,849.67 kWh, p2 = 20%	Estimated based on Görgens (2019)			0.0%
Milling/drying machine electric capacity[3] (Alternative II)	Discrete/ user-defined	**x1 (22 kWh/100 kg) = 21,156.04 kWh**, p1 = 80%, x2 (larger size, −20%/kg input, 17.6 kWh/100 kg) = 16,924.84 kWh, p2 = 20%	Estimated based on Görgens (2019)			0.0%
Selling price pomace	Uniform	**Min €0.50/kg,** Max €9.00/kg	Estimated based on Brunneby (2017)		33.5%	66.9%

Original input variables used in the three scenarios are written in bold and further manifestations of these input variables used in the Monte Carlo simulation in standard type.

[1] Correlation of −0.7 assumed between *BC production price* and *Total harvest yield*.

[2] calculated based on €8.50/h statutory minimum wage (2016) including employer's social contribution (BMJV, 2014; Jung, 2018).

[3] Correlation of −0.5 assumed between *Price milling/drying machine* and *Milling/drying thermal/electric capacity*.

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10,000 iterations to generate enough random numbers so that an adequate validity of the uncertainty analysis was guaranteed (Oracle, 2012).

The resulting forecast for all scenarios is shown as boxplot diagram in Fig. 6 and as frequency distribution in Fig. 7. The output distribution is in all cases almost normally distributed and continuous, although the variance increases in the alternative scenarios. The mean value in the baseline scenario is €352,610 with a standard deviation of €114,521 and, thus, lower than the base case (see Table A.1). The forecast profit ranges between €181,974 and €568,774 with a certainty of 90%. To our surprise, achieving a profit of €427,146 (base case) is less likely as the certainty level is only 22.9%. Sensitive assumptions in the baseline scenario are *water-juice ratio* (47.0%), *BC production price* (−27.9%), and *selling price juice* (24.5%) as they explain most of the variance in the forecast value (see Table 7, contribution to variance).

The mean value in alternative scenario I accounts for €431,965 with a standard deviation of €134,245. With a certainty of 55.9%, one can be confident of making a net profit of at least €399,476 (base case) and thus possibly generating a competitive advantage over the baseline scenario. Assumptions in alternative scenario I that have a strong effect on the forecast are *water-juice ratio* (33.7%), *selling price pomace* (33.5%), *BC production price* (−16.0%), and *selling price juice* (14.9%). The mean value in alternative scenario II accounts for €547,015 with a standard deviation of €177,543. A minimum net profit of €399,824 (base case) can be achieved with a certainty of 77.5%, which is even higher than in alternative scenario I. Assumptions most relevant for the forecast are *selling price pomace* (66.9%), *water-juice ratio* (18.7%), *BC production price* (−7.3%), and *selling price juice* (6.2%). All other input variables can be neglected as they represent less than ±1.0% of the variance.

Within SPSS (IBM Corp., 2015), it should be investigated whether the mean net profits actually differ statistically from each other. Since testing the homogeneity of variances (Levene test) turned out to be significant for all three groups (p = 0.000), a Kruskal-Wallis H test (Kruskal and Wallis, 1952), a rank-based non-parametric test, was conducted to compare the results. The test revealed that there was a statistically significant difference in the net profit results between the different scenarios, $\chi^2(2) = 6709.446$, p = 0.000, with a mean rank of 10,068.55 for the baseline scenario, 14,836.23 for alternative scenario I, and 20,096.72 for alternative scenario II (see Table A.2).

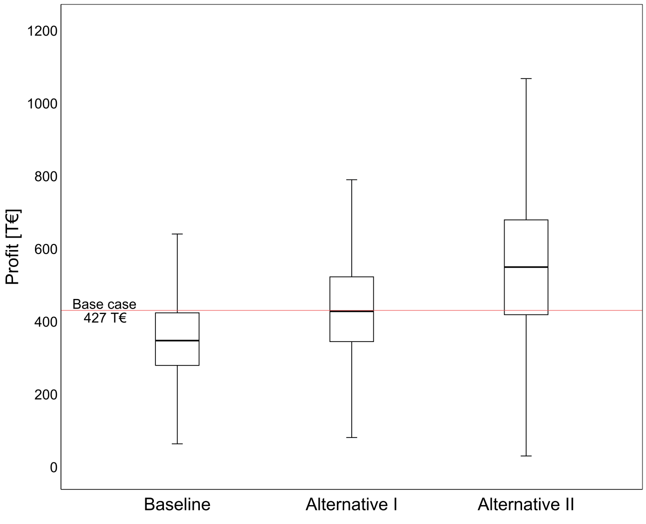

Fig. 6. Boxplot diagrams without outliers.

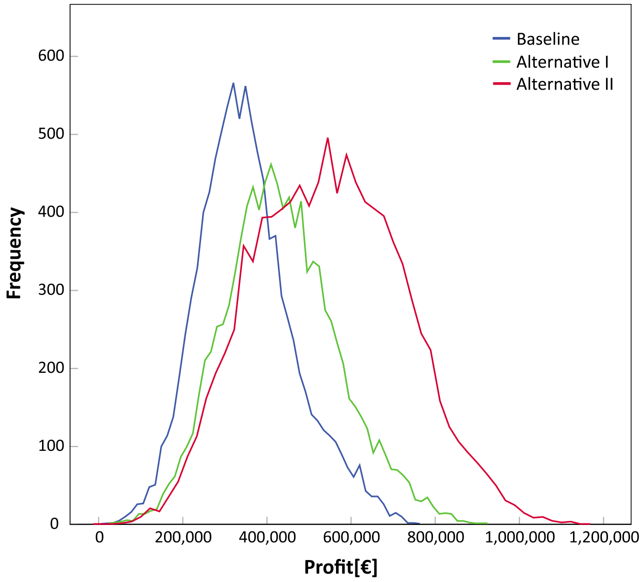

Fig. 7. Frequency distributions without outliers.

4.4. Integrating the economic and environmental performance of berry pomace

Via parameter variation of the assumption *selling price pomace*, we discovered that the selling price has to be €1.50/kg in alternative scenario I and €1.00/kg in alternative scenario II, respectively, to achieve approximately the same profit of €427K as in the baseline scenario, even though we already know that this profit is less likely there and possibly even lower. With a selling price of €2.00/kg pomace we can achieve a commensurate profit increase of 3.2% (€441K) in alternative scenario I and 13.0% (€483K) in alternative scenario II. Such a price is only feasible for a high-quality product that at best is organically produced, still contains a high amount of bioactive compounds after processing, is incorporated in a way that it does not impair the properties of the final consumer product, and that is aimed at highly profitable market segments such as functional food, pharmaceuticals, or cosmetics. For the GWP, any further material use of the berry pomace makes sense. In alternative scenario II, we even reach climate mitigation by partially substituting climate-relevant staple-foods (see Fig. 8).

With this study, we have demonstrated the interoperability of MFCA with environmental assessments and the feasibility of the integrated approach illustratively for a case in the food sector. Despite having to respect certain confidentiality requirements, a solid database could be compiled in cooperation with the regional juice producer. We have also shown the economic and environmental benefits for juice producers which evolve from the upcycling of berry pomace. Moreover, these corporate benefits translate into societal benefits such as less emissions and healthier food products. Customers of today are more and more interested in the origin of food, the conditions under which it is produced, the associated environmental impacts, and the exact ingredients of processed food (Bravo et al., 2013). MFCA, together with LCA and social assessments, delivers many answers to these customer requests and can thus contribute to greater awareness and transparency in the food sector.

Limitations of the chosen approach lie, on the one hand, in the linear modeling neglecting dynamic and non-steady processes in nature, such as the influence of climate change on the quantitative and qualitative production of berries and spatiotemporal

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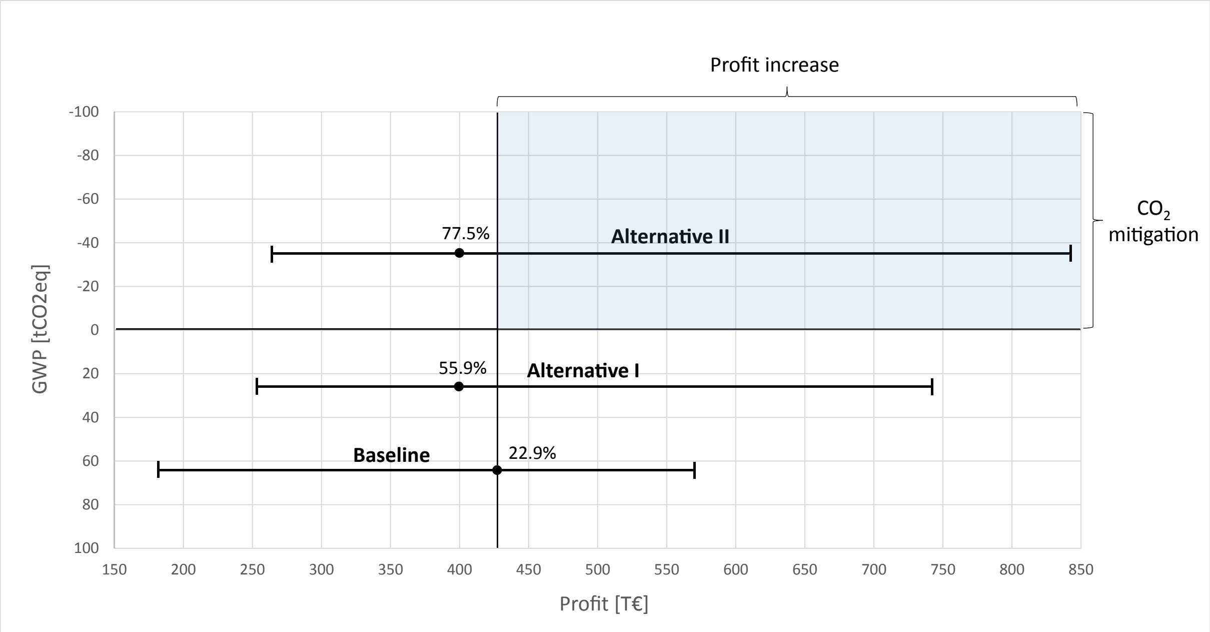

Fig. 8. Portfolio diagram showing the total GWP (fixed) and profit (90% certainty level) for three scenarios. The original results from the MFCA analysis are depicted as black dots including the corresponding certainty level.

variabilities. On the other hand, there is untapped optimization potential in the processing chain, particularly at the stage of pomace treatment and storage including all associated logistics, where sophisticated mathematical programming is imperative. This encompasses the development of alternative scenarios, e.g. direct drying or outsourcing of treatment. A further requirement for future studies would be the improved transferability of results by examining other juice producers and regions, given that berries are traded and processed globally.

Procurement of new, resource-efficient technologies and investment in cleaner production can make a manufacturing company more competitive and resilient, but it may also spur the technological development of resource- and energy-efficient technologies on the supply side. In berry juice production, quantitative material losses are comparatively low and non-hazardous, raising the question of whether MFCA is necessary here. According to Christ and Burritt (2015) and Lang et al. (2005), MFCA can provide useful information as an ad-hoc analysis, e.g. for deciding on investing in the expansion of a production line or extension of the product portfolio, even if it is not part of the existing cost accounting system of the company. This statement seems to be supported by our analysis which delivers quantitative results in the form of monetary values to which corporate decision makers are accustomed. However, we must concede that also this MFCA case study was action-based, i.e. initiated by researchers. Whether the results will ultimately lead to organizational changes and new investments is a question to be addressed in a follow-up investigation. Finally, a successful implementation of MFCA in daily-business operations, especially in small and medium-sized enterprises (SME), requires a straightforward approach with integrated databases and software solutions, e.g. a better connection of Enterprise Resource Planning (ERP) tools with environmental information systems (Christ and Burritt, 2015; Heupel and Wendisch, 2003).

Furthermore, the question arose as to whether legal aspects could hamper investments in pomace upcycling. As business models aiming at the extraction of pectin from apple pomace have already proven successful, the authors do not expect unresolvable legal restrictions for the use of berry pomace. Nevertheless, it is important that berry pomace intended to be used in food is treated and stored according to good agricultural and manufacturing practice, meets the requirements for product purity, and is subject to proven concepts of food safety such as Hazard Analysis and Critical Control Points (HACCP). Pursuant to the European Novel Food Regulation, new foods produced from plants or their parts do not need an extra approval as long as it is produced from raw materials already used traditionally for human consumption to a significant degree in the EU before May 15th, 1997 (EC, 2015b); this may apply to food creations with isolated residues (Dietz, 2008), but requires a case-by-case examination. Ultimately, it is the responsibility of the manufacturer to check that their product complies with given registration and labelling requirements and to liaise with the competent authority if in doubt.

In view of the current situation of the global ecosystems, a more responsible use of natural resources is urgently needed. In a recent publication from the Intergovernmental Science-Policy Platform on Biodiversity & Ecosystem Services (IPBES, 2019) it is stated that the productivity of 23% of the global land area is in decline due to degradation, and that mostly regulating ecosystem services, e.g. soil organic carbon, have deteriorated over the last decades. Land use changes caused by agricultural expansion are the largest driver of this negative development. Among the proposed key actions to simultaneously safeguard food resources and biodiversity are the general avoidance of food waste, the transformation of supply chains, and a better access to sustainable and healthy food. Against this background, product innovations in the food sector, as described in this study, can not only contribute to mitigating climate change, but also relieve the burden on natural biomass production systems by avoiding and upcycling food waste. However, further research is needed to assess the relief effect and to translate ecosystem services such as soil functions or food provisioning functions into decision making.

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5. Conclusion

MFCA is a powerful tool when it comes to the identification of resource optimization potentials in production systems. In the case of inefficiencies in berry juice production, it is not so much a process engineering issue but a matter of losing value in the form of health-promoting phytochemicals and fibers naturally located in and directly under the skin rather than in the pulp of berry fruits. This analysis could show that the environmental performance of the main product, 520,483 1L-bottles of black currant juice, in terms of GWP benefits from the upcycling of the pomace to a marketable product. Whereas we calculated a GWP of 0.12 kg CO_2eq/L for the baseline scenario, lower values of 0.05 kg CO_2eq/L (alternative I) and −0.07 kg CO_2eq/L (alternative II) were achieved for the alternative multi-output scenarios. From the economic side, we could not demonstrate a reasonable amortization of the additional investment costs, which are needed to transform the fresh pomace into a stabilized and saleable product, in the scenario analysis. Against the calculated profit of €427K in the baseline scenario, we achieved a deficit of €27K in the alternative scenarios. However, the scenario and uncertainty analysis revealed that there are promising strategies to increasing the profit. First, it is recommendable to additionally use apple pomace as most of the juice producers have apple juice in their portfolio. Second, it is decisive to develop a high-quality and ideally organic product that can be used as a functional food supplement or in pharmaceutical and cosmetic applications, because only there can an attractive selling price of at least €2.00/kg pomace be achieved, corresponding to an overall profit increase of 13.0%. A basic prerequisite, however, is that companies incorporate MFCA into their management control system to translate its overarching goal of resource use optimization into corporate strategy. With this study we want to go beyond the mere discussion of the theoretical concept behind MFCA by demonstrating its practical implications. Our findings, in particular, help to better understand the key issues and challenges associated with investing in berry pomace processing technologies and thus will support the practical implementation of cleaner production concepts in the juice industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

BC	black currant
CH	Switzerland
CO_2eq	carbon dioxide equivalent
DE	Germany
EMA	environmental management accounting
EoL	end-of-life
ERP	enterprise resource planning
GWP	global warming potential
HACCP	hazard analysis and critical control points
HDPE	high density polyethylene
K	thousand
LCA	life cycle assessment
MFCA	material flow cost accounting
PAN	polyacrylonitrile
pa	physical allocation
PDCA	plan-do-check-act cycle
QC	quantity center
RER	Europe
SAN	styrene acrylonitrile
SDG	sustainable development goal
SME	small and medium-sized enterprise
ua	user-defined allocation
VAT	value added tax

Appendix A

Table A.1
Descriptive statistics for simulated net profit in three scenarios.

Scenario	N	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness	Std. Error	Kurtosis	Std. Error
Baseline	10,000	12,096	757,643	352,610.31	114,520.875	13,115,030,811.361	.471	.024	.210	.049
Alternative I	10,000	25,968	924,911	431,965.23	134,245.394	18,021,825,914.604	.301	.024	-.017	.049
Alternative II	10,000	−4815	1,177,267	547,014.58	177,542.765	31,521,433,314.352	.129	.024	-.371	.049
Valid N (listwise)	10,000									

Table A.2
Levene test and Kruskal Wallis H test results for simulated net profits in three scenarios.

Statistical test		Netprofit	df1	df2	Sig.
Levene test	Based on mean	1093.618	2	29,997	.000
	Based on median	1092.719	2	29,997	.000
	Based on median and with adjusted df	1092.719	2	27,623.114	.000
	Based on trimmed mean	1097.070	2	29,997	.000
Mean ranks	Baseline	10,068.55			
	Alternative I	14,836.23			
	Alternative II	20,096.72			
Kruskal-Wallis H	Grouping variable: scenarios	6709.446	2		.000

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118946.

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