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Optimising agri-food supply chains: Managing food waste through harvest and side-stream valorisation

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ABSTRACT

The importance of reuse and valorisation as a means to enhance sustainable production practices, by reducing waste streams through the recovery of resources in the chain, is increasingly recognised. Confronted with new challenges in the context of climate change, the food and agricultural sector stands to benefit, in particular, from valorising (edible) side streams, such as unharvested crop parts and vegetable peels, that are often overlooked by consumers. Focusing on side-stream valorisation strategies within food processing facilities, this research develops a mixed-integer optimisation model to support decision-makers in determining an optimal product portfolio and processing configuration. This model is solved for two key performance indicators, considering both the economic and the environmental impact, in the form of total profit and exergy loss. Examining potential trade-offs between the two objectives, we present a real-life case study from a carrot processing company. We explore several scenarios and case settings to investigate the impact of various factors on the potential of side-stream valorisation. The findings from our analysis demonstrate that side-stream valorisation seems to be generally well aligned with profit maximisation, while it is not always beneficial from an environmental impact perspective.

1. Introduction

Despite an increasing need for food to meet the demand of current and future generations (FAO, IFAD, UNICEF, WFP & WHO, 2022), roughly one-third of the global food supply continues to be wasted (FAO, 2019). This food waste accounts for about 7% of global greenhouse gas (GHG) emissions, significantly contributing to climate change (FAO, 2013, 2019), thus, further jeopardising future food security. Reducing food waste and eliminating its causes is, as such, an essential step towards achieving food security and advancing sustainable development. An important consideration in this context is the quality of products (Raak et al., 2017), which is generally defined by the physical properties of food such as texture, flavour, and the microbial state (Akkerman et al., 2010). The perception of these properties plays a crucial role in terms of waste, as products with lower quality are often viewed as less desirable by consumers, resulting in lower demand and profitability. Consequently, these products are more likely to be wasted (de Hooge et al., 2018; Porter et al., 2018; FAO, 2019). In addition to the waste caused by consumer behaviour, a substantial amount of food is lost due to quality decay and inadequate handling during storage and transportation activities (Raak et al., 2017; FAO, 2019). To compensate for such losses and other factors that may negatively affect yields, farmers often produce more than required (FAO, 2011). This oversupply, in turn, leads again to more food waste due to product quality decay, which inhibits the use of this supply in later periods (Akkerman and Cruijssen, 2024).

Therefore, instead of adjusting their production volumes, farmers should make better use of (currently unused) side streams to satisfy the increasing demand for food and, thereby, generate new revenues. While the most preferred valorisation option from the perspective of food security would be a conversion to food products suitable for human consumption (Teigiserova et al., 2020), unless the resource characteristics dictate otherwise (Scherhaufer et al., 2020), side streams are often still left on the land, used as fertiliser, or converted to feed (Hartikainen et al., 2017; Bockstael et al., 2019). However, many side streams such as cauliflower leaves, Brussels sprouts stalks, and pea foliage are perfectly edible, even though overlooked by consumers due to their unfamiliarity, resulting in a low likelihood of consumption (Berndtsson et al., 2020; Mythili et al., 2021; Sedlar et al., 2021). To enhance

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this likelihood of consumption, surplus food and edible side streams may have to be processed into products that last longer and are more familiar to consumers, such as soups, sauces, and juices, for which specific quality attributes are often less important (de Hooge et al., 2018).

To address these challenges, food producers should consider (re-)designing their product portfolios based on the supply of harvested resources rather than solely on customer demand, creating more supply-driven agri-food chains that consider potential surplus and side streams. Generating value from underutilised resources, this supply-driven approach holds the potential to reduce food waste and promote future food security, contributing to the development of a more sustainable and efficient food system.

Making good decisions regarding the product portfolio can, however, be challenging due to the abundance of available processing options, product choices, and quality considerations. In response to the pressing need to reduce food waste and improve sustainability in agri-food supply chains, this paper explores the potential of side-stream valorisation as a strategic approach to optimise resource efficiency. Our objective is, thus, to develop strategies for agri-food supply chain design that facilitate optimal decision-making for a given supply while adhering to the limits of customer demands. More specifically, we aim to identify the optimal product portfolio, product flows, and the underlying processing operations from both an economic and environmental point of view. The scope of our research includes a network of harvesting, processing, and customer locations, in which we study the transformation of agricultural resources at processing facilities using a set of recipes, while also accounting for waste in the form of unused supply, unused outputs, and waste generated during processing and shipment. This research thus seeks to address the following research questions:

1. **How can an optimal product portfolio be designed for agri-food supply chains, balancing economic and environmental goals while incorporating waste considerations?**
   In response to this question, our study proposes a bi-objective mixed-integer optimisation model that maximises profits and minimises environmental impacts. As an environmental metric, our model considers different types of exergy losses arising in the chain, thereby contributing to the field of food valorisation, as this approach is scarcely explored in current research (Wei et al., 2024).
2. **How can product portfolio optimisation models account for more flexibility in product transformations?**
   To answer this research question, we accommodate a broad spectrum of recipes in our model, by allowing product substitution and flexibility in further processing intermediate products, achieved by grouping inputs and outputs into categories. Furthermore, unlike traditional models, our approach explicitly accounts for diverse quality transformations, including both quality improvement and degradations, by integrating specific parameters that capture these changes. Thereby, we bridge the gap in existing models which fail to capture more flexible operations, as indicated by Stefansdottir and Grunow (2018) and Banasik et al. (2017b), enabling practical implementation in diverse supply chain contexts.
3. **What are the best strategies for valorising agricultural supplies from both an economic and environmental perspective?**
   By applying our model to a real-life case study while exploring trade-offs between economic and environmental goals through a Pareto analysis, we obtain answers to this research question. Our findings reveal that food valorisation strategies align well with economic objectives but may not always yield environmental benefits. Instead, the most effective strategy to minimise environmental impacts is to improve processing efficiencies. These insights highlight the complexity of decision-making in food waste management and provide valuable guidance for supply chain and portfolio (re)design, with broader applicability beyond the food sector.
4. **What are the economic, environmental, and waste-related implications of demand flexibility?**
   By exploring various case settings and scenarios, the study examines how flexible demand, both in terms of product quantity and type, can influence economic performance, environmental sustainability, and waste reduction strategies. This approach reveals that supply chains with greater demand flexibility tend to have lower environmental impacts, as surplus products can be used more efficiently, potentially increasing profits. By combining supply- and demand-driven approaches, this study offers a fresh perspective on supply chain (re-)design to optimise resource use while ensuring environmental and economic sustainability under consideration of resource availability.
5. **What are the economic, environmental, and waste-related implications of incorporating side-stream-based products into the product portfolio?**
   By developing a case study that explores additional valorisation options through portfolio extension with side-stream-based products, the study aims to uncover the economic and environmental impacts of utilising previously underused resources. This approach shows potential for new revenue streams and reduced waste in agri-food supply chains.
6. **How do data fluctuations influence the design and feasibility of an optimal product portfolio?**
   Recognising the variability inherent in real-world supply chains, we perform additional extensive analyses on various scenarios to assess how data fluctuations affect optimal decision-making. These analyses provide insights into the robustness and adaptability of the proposed model under different conditions.

By addressing these research questions, our study makes significant contributions to the literature on food waste reduction and sustainable supply chain management. The remainder of the paper is structured as follows. Section 2 provides an overview of the related literature, while Section 3 describes the studied problem. The mathematical model is outlined in Section 4, followed by a detailed description of the experimental design in Section 5, introducing the real-life case study as well as the considered scenarios and case settings. The results of these numerical experiments are then presented in Section 6, and discussed in Section 7, before concluding the paper in Section 8.

2. Literature review

Agri-food supply chains have received growing attention in the scientific literature in recent years (as emphasised by the reviews of Bloemhof and Soysal (2017), Nematollahi and Tajbakhsh (2020), Agnusdei and Coluccia (2022), and Yadav et al. (2022)), with the review paper of Yadav et al. (2022) describing food waste as one of the main challenges in feeding the growing world population. Operations Research (OR) models provide a quantitative approach to tackle this challenge by optimising decision-making processes within supply chains. However, OR models that explicitly address and incorporate the notion of food waste are scarce (Moraes et al., 2021), with existing research in this domain focusing primarily on waste management at retail and consumer levels (see, e.g., Lee and Tongarlak, 2017; Buisman et al., 2019; Beullens and Ghiami, 2022; Ganguly and Robb, 2022; Hezarkhani et al., 2023), while overlooking the earlier stages of the supply chain.

Focusing on valorisation aspects at the production stage, the authors of Lim et al. (2013) present a mixed-integer optimisation model that determines the optimal resource allocation, process setup, and portfolio selection for the efficient use of rice by-products for food, feed, and energy applications. Analysing similar decision aspects within sugar beet processing, Jonkman et al. (2017) consider side streams and quality in some scenarios without explicitly integrating this into their mixed-integer optimisation model. Other studies, such as those by Shukery et al. (2016) and Kasivisvanathan et al. (2012), incorporate the aspect of waste management more explicitly by introducing decision variables that track waste in their optimisation models for palm oil mills. The study of Banasik et al. (2017a), focusing on food waste valorisation in the bread chain, also introduces specific decision variables to track waste, in addition to applying fixed waste fractions to account for losses during production and at the retail outlet. Their bi-objective model considers both the total profit and the environmental impact of waste in the form of exergy losses. Proposing a bi-objective model with exergy and costs, Banasik et al. (2017b) adds quality considerations using fixed values by distinguishing between premium and low-quality mushrooms, proposing a mixed-integer formulation to optimise a closed-loop supply chain. Considering gradual quality decay by tracking products' remaining shelf lives and using a minimum shelf life requirement in the demand constraints of their model, Esteso et al. (2021) optimise harvest, facility location, shipment, and inventory decisions in their mixed-integer optimisation model for a fruit and vegetable supply chain while associating a penalty cost for waste.

Most of these studies take a demand-driven approach, while studies with a supply-driven focus are still rare. One of the few studies considering a supply-driven approach is presented by Stefansdottir and Grunow (2018), who develop a two-stage stochastic optimisation model in which all supply is directed to the production facilities, and overproduction results in a lower profit margin. The authors also account for by-products and waste fractions in the process and transport stages, yet optimise for profit only. Optimising for greenhouse gas (GHG) emissions as well as job opportunities and costs, Krishnan et al. (2022) formulate a robust multi-objective mixed-integer optimisation model to solve a supply-driven valorisation problem under consideration of product quality and shelf-life for a mango supply chain network. This network consists of farmers, processing plants, distributors, and markets as well as waste recovery plants that convert mango side streams. However, while deciding on product flows, inventory, and facility locations, the proposed formulation does not allow much flexibility regarding ingredient or processing option selection. Moreover, the authors consider the demand for side-stream-based products unlimited, which may not be realistic in a practical setting.

This literature overview (also summarised in Table 1) shows that previous OR literature has addressed various aspects of waste reduction in agri-food supply chains. Nonetheless, there is a lack of more explicit consideration of waste reduction strategies and quality changes in optimisation models. From Table 1, we see, moreover, that studies increasingly incorporate environmental objectives, such as emissions (Kasivisvanathan et al., 2012; Shukery et al., 2016; Krishnan et al., 2022), water pollution (Kasivisvanathan et al., 2012; Shukery et al., 2016) and exergy (Banasik et al., 2017a,b). Measuring the amount of effort or work needed to produce a product (Apaiah et al., 2006), exergy presents one of the best metrics to quantify the value/impact of waste and side streams (Zisopoulos, 2016). Using total exergy loss as a key performance indicator to measure the environmental impact of waste, our work contributes to the existing literature by extending the boundaries of most recent studies to consider intermediates and by-products while including substitution options on the production and demand side. In addition, we explicitly incorporate quality changes, considering the possibility of quality increases, which has mostly been neglected in previous studies. This is important as quality improvements can contribute significantly to waste reduction strategies, e.g., by extending shelf life through canning. In addition, a supply-driven approach is still scarce in existing studies despite its crucial role in preventing upstream losses.

3. Problem description

Addressing the current gaps in the literature, this research aims to determine an optimal product portfolio for a crop processing company under consideration of waste and product side streams. In this context, we assume a production network consisting of harvest, process, and customer locations (as shown in Fig. 1). The harvest locations represent agricultural production locations, supplying resources of different qualities. Depending on the characteristics of these resources, they can be either sold directly to the customers or processed into other products.

Processing occurs at process locations (see Fig. 1), and involves the conversion of one or multiple inputs into one or multiple outputs according to recipes, which specify the relation between these inputs and outputs. As such, these recipes determine the various outputs of a process, consisting of the main product (denoted as the main output) as well as the by-products. In terms of inputs, recipes may use outputs from process locations, as well as fresh resources supplied directly from the harvest locations or obtained by purchasing at a cost proportional to harvesting costs (Assumption 1). Depending on the processing requirements, the considered recipes specify furthermore the required input quality to obtain a desired output quality. It should be noted that the quality of products during processing and shipment may decrease due to quality decay and increase as a result of processing operations such as canning or pasteurisation. Different process locations may be selected for the process operations, which may incur a setup cost (Assumption 2). Once processed, products can be used as inputs for other processes or sold and shipped directly to the customer locations, assuming transport is not capacitated (Assumption 3).

The customer-dependent demand is specified for product categories, encompassing a group of products that can substitute for each other, thus providing more flexibility in serving the demand. For example, customers may request radishes while being indifferent about the colour. At the same time, customers may be flexible in some cases regarding the demanded quantity, specifying an acceptable range rather than an exact quantity that needs to be supplied (Assumption 4).

Based on these specifications, the processor needs to determine the optimal product portfolio, product flow, and processing operations under consideration of the associated product waste. Waste occurs, in this context, during shipment and processing in the form of a fixed loss percentage, while unused supplied resources and unused outputs are also classified as waste (Assumptions 5 and 6). Considering different objectives, the overall waste is then accounted for in the environmental impact objective, using total exergy loss as the performance indicator. In addition, we optimise the economic performance of the system by maximising the total profit.

To summarise, our proposed model is based on the following set of assumptions, which are motivated by practical observations as well as the scientific literature (Jonkman et al., 2017; Kasivisvanathan et al., 2012; Banasik et al., 2017b; Esteso et al., 2021):

Assumption 1. Purchasing costs are linearly proportional to harvesting costs.

Assumption 2. The production of an output incurs a setup cost.

Assumption 3. Transportation is assumed to be non-capacitated.

Assumption 4. Customer demand is specified within a given range.

Assumption 5. Supplied resources that are not processed are considered waste.

Assumption 6. Produced outputs that are not sold to customers are considered waste.

Table 1
Studies on decision models for product portfolio problems.

Authors	Case study	Sustainable objective	Quality			Waste			Supply-driven	Demand-driven
			Fixed values	Gradual decay	Quality increase	Fixed fraction	Unused products	Shelf life		
Lim et al. (2013)	Rice mill								✓	✓
Jonkman et al. (2017)	Sugar beet								✓	
Kasivisvanathan et al. (2012)	Biorefinery	Environmental burden					✓			✓
Shukery et al. (2016)	Biorefinery	Water contamination, GHG emissions					✓			✓
Banasik et al. (2017a)	Bread	Exergy				✓	✓			✓
Banasik et al. (2017b)	Mushroom	Exergy	✓				✓			✓
Esteso et al. (2021)	Fruit and vegetables			✓				✓		✓
Stefansdottir and Grunow (2018)	Dairy		✓			✓			✓	
Krishnan et al. (2022)	Mangoes	GHG emissions, jobs		✓		✓	✓		✓	✓
Our work	Vegetables	Exergy	✓	✓	✓	✓	✓		✓	✓

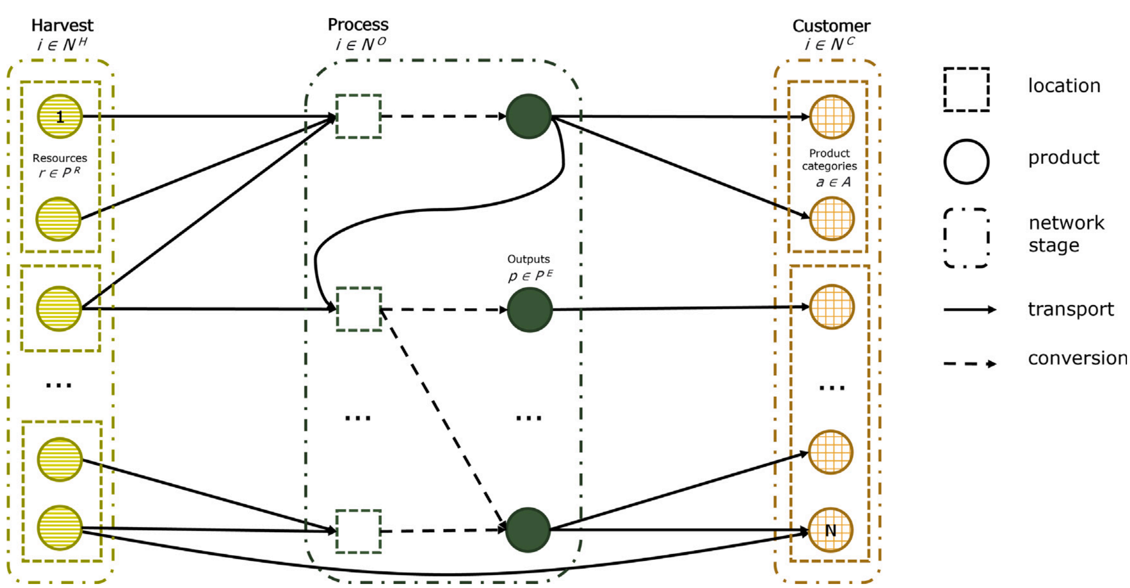


Fig. 1. The schematic illustration of a supply chain network of a crop processor with light-green harvest locations (left), dark-green candidate process locations (middle), and beige customer locations (right). Black arrows show the product flows. Dashed arrows indicate the conversion of inputs to outputs.

4. Model formulation

Based on the assumptions outlined in Section 3, the problem is formulated as a bi-objective mixed-integer optimisation model. This section presents the mathematical formulation of the model, providing a detailed description of the constraints as well as the key performance indicators. The nomenclature can be found in Table 2. Note that we improve the model's efficiency by using a sparsified model that considers only the variables associated with valid combinations of indices. For ease of notation, we do not include this requirement in the mathematical formulation.

4.1. Constraints

This section presents the model's constraints, starting with the constraints ensuring that products are converted correctly during processing. These constraints ensure that resource and product inputs are proportional to the generated outputs (including side streams) while allowing for flexibility in the input selection by grouping inputs into broader product categories. We want to emphasise in this context that products can be produced using supplied resources originating at farm locations or intermediates generated at other processing lines. Furthermore, the parameters l, ϕ, λ, and γ ensure this conversion happens according to the recipes. Deducting waste from transport and processing, we then obtain for all input categories $c \in \mathcal{C}_p$, all main outputs $p \in \mathcal{P}^{\mathcal{P}}$, all qualities $q' \in \mathcal{Q}$, all locations $j \in \mathcal{N}^O$, all outputs $e \in \mathcal{E}_p$, and all qualities $q'' \in \mathcal{Q}$ for which $\pi^{eq''}_{jpq'} = 1$,

$$\underbrace{\sum_{i\in\mathcal{N}^H}\sum_{r\in\mathcal{P}^{\mathcal{R}}}\sum_{q\in\mathcal{Q}}\left(1-\omega^T_{ijr}\right)\left(1-\omega^O_{jc}\right)l^{eq''}_{jrpq'}\phi^{jpq'}_{irq}\phi^{jeq''}_{irq}\lambda_{rcp}Y^{jpq'}_{irq}}_{\textbf{resources}} + \underbrace{\sum_{i\in\mathcal{N}^O}\sum_{r\in\mathcal{P}^{\mathcal{E}}}\sum_{q\in\mathcal{Q}}\left(1-\omega^T_{ijr}\right)\left(1-\omega^O_{jc}\right)l^{eq''}_{jrpq'}\phi^{jpq'}_{irq}\phi^{jeq''}_{irq}\lambda_{rcp}V^{jpq'}_{irq}}_{\textbf{intermediates}} = \gamma_{cpq'}X_{jeq''}. \tag{1}$$

To enforce that the output quantity cannot exceed the capacity, we state for all outputs $p \in \mathcal{P}^{\mathcal{E}}$, all qualities $q \in \mathcal{Q}$, and all process locations $i \in \mathcal{N}^O$,

$$X_{ipq} \leq \eta^O_{ip} Z_{ipq}. \tag{2}$$

In addition, the production hours required to process the inputs, originating from harvest or process locations, cannot exceed the total available hours. Note that transport waste is deducted from the input quantity to account for losses during transport. Moreover, we express the capacity based on inputs using the maximum processing capacity per time unit. For example, a machine can maximally process x kg of yellow carrots per hour. Constraint (3) ensures that this capacity is not exceeded, and holds for all process locations $j \in \mathcal{N}^O$,

$$\sum_{i\in\mathcal{N}^H}\sum_{r\in\mathcal{P}^{\mathcal{R}}}\sum_{p\in\mathcal{P}^{\mathcal{E}}}\sum_{q,q'\in\mathcal{Q}}\frac{1}{\eta^I_{jr}}\left(1-\omega^T_{ijr}\right)Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O}\sum_{r,p\in\mathcal{P}^{\mathcal{E}}}\sum_{q,q'\in\mathcal{Q}}\frac{1}{\eta^I_{jr}}\left(1-\omega^T_{ijr}\right)V^{jpq'}_{irq} \leq \xi_j. \tag{3}$$

Moreover, the quantity of products sent to a customer's location should equal the quantity used to satisfy the customer's demand. Note that input quantities, originating from harvest or process locations, are once again adjusted to account for transport waste. To ensure this, we introduce Constraint (4), which holds for all products $p \in \mathcal{P}$, all qualities $q' \in \mathcal{Q}$, and all customer locations $j \in \mathcal{N}^C$,

$$\sum_{i\in\mathcal{N}^O}\sum_{q\in\mathcal{Q}}\left(1-\omega^T_{ijp}\right)\phi^{jpq'}_{ipq}O^{jq'}_{ipq} + \sum_{i\in\mathcal{N}^H}\sum_{q\in\mathcal{Q}}\left(1-\omega^T_{ijp}\right)\phi^{jpq'}_{ipq}H^{jq'}_{ipq} = \sum_{a\in\mathcal{A}}F_{pqaj}. \tag{4}$$

The quantity of products used to satisfy the demand should fall, furthermore, within the acceptable range defined by the demand's lower and upper bounds. To ensure this, we introduce Constraint (5), which holds for all customer locations $j \in \mathcal{N}^C$ and all product categories $a \in \mathcal{A}$,

$$\delta^L_{ja} \leq \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}F_{pqaj} \leq \delta^U_{ja}. \tag{5}$$

When products are sold, we need to ensure that only the products specifically selected for sale are used to satisfy the demand for a product category at a customer location. For this, we introduce Constraint (6), which holds for all products $p \in \mathcal{P}$, all qualities $q \in \mathcal{Q}$, all customer locations $j \in \mathcal{N}^C$, and all product categories $a \in \mathcal{A}$.

$$F_{pqaj} \leq \delta^U_{ja} S_{pqaj}. \tag{6}$$

At the same time, we need to ensure that customer demand for product categories can only be satisfied by products in this category with the appropriate product characteristics. For this purpose, we introduce Constraint (7), which holds for all products $p \in \mathcal{P}$, all qualities $q \in \mathcal{Q}$, all customer locations $j \in \mathcal{N}^C$, and all product categories $a \in \mathcal{A}$.

$$S_{pqaj} \leq \alpha_{pqaj}. \tag{7}$$

Furthermore, we must ensure that only one product with appropriate product characteristics is selected to satisfy the demand for a product category at a customer location. Therefore, we introduce Constraint (8), which holds for all product categories $a \in \mathcal{A}$ and all customer locations $j \in \mathcal{N}^C$ if $\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\alpha_{pqaj} = 1$,

$$\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}}\alpha_{pqaj}S_{pqaj} = 1. \tag{8}$$

Finally, we track the waste in the system, with Constraint (9) calculating the waste quantity occurring during transportation from harvest or process locations to any processing location $j \in \mathcal{N}^O$ for any product $p \in \mathcal{P}$,

$$W^{T^o}_{jp} = \sum_{q,q'\in\mathcal{Q}}\Big(\sum_{i\in\mathcal{N}^H}\sum_{r,p\in\mathcal{P}}\omega^T_{ijr}Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O}\sum_{r,p\in\mathcal{P}}\omega^T_{ijr}V^{jpq'}_{irq}\Big). \tag{9}$$

while Constraint (10) calculates the waste occurring during transportation from harvest or process locations to any customer location $j \in \mathcal{N}^C$ for any product $p \in \mathcal{P}$,

$$W^{T^c}_{jp} = \sum_{q,q'\in\mathcal{Q}}\Big(\sum_{i\in\mathcal{N}^H}\sum_{r\in\mathcal{P}}\omega^T_{ijr}H^{jq'}_{irq} + \sum_{i\in\mathcal{N}^O}\sum_{r\in\mathcal{P}}\omega^T_{ijr}O^{jq'}_{irq}\Big). \tag{10}$$

The waste during processing is then calculated by Constraint (11) as a proportion of the input quantities from harvest and processing locations, while accounting for transport waste. This constraint applies to all process locations $j \in \mathcal{N}^O$ and all outputs $p \in \mathcal{P}^{\mathcal{E}}$,

$$W^P_{jp} = \sum_{i\in\mathcal{N}^H}\sum_{c\in\mathcal{C}_p}\sum_{r\in\mathcal{P}^{\mathcal{R}}}\sum_{q,q'\in\mathcal{Q}}\left(1-\omega^T_{ijr}\right)\omega^O_{jc}\lambda_{rcp}Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O}\sum_{c\in\mathcal{C}_p}\sum_{r\in\mathcal{P}^{\mathcal{E}}}\sum_{q,q'\in\mathcal{Q}}\left(1-\omega^T_{ijr}\right)\omega^O_{jc}\lambda_{rcp}V^{jpq'}_{irq}. \tag{11}$$

Furthermore, the difference between the supplied or purchased quantities compared to used resource quantities for shipment to processing or customer locations is considered an unused supply and, thus, treated as waste (see Assumption 5). We introduce Constraint (12) to calculate this waste for all resources $r \in \mathcal{P}^{\mathcal{R}}$, all qualities $q \in \mathcal{Q}$ and all harvest locations $i \in \mathcal{N}^H$,

$$U^S_{irq} = \beta_{irq} + B_{irq} - \Big(\sum_{j\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{E}}}\sum_{q'\in\mathcal{Q}}\phi^{jpq'}_{irq}Y^{jpq'}_{irq} + \sum_{j\in\mathcal{N}^C}\sum_{q'\in\mathcal{Q}}\phi^{jpq'}_{irq}H^{jq'}_{irq}\Big). \tag{12}$$

Similarly, the difference between the produced and used output quantities, shipped to processing or customer locations, is considered an unused output and, thus, waste (see Assumption 6). Considering quality, this difference is calculated using Constraint (13), which holds for all outputs $r \in \mathcal{P}^{\mathcal{E}}$, all qualities $q \in \mathcal{Q}$ and all process locations $i \in \mathcal{N}^O$,

$$U^T_{irq} = X_{irq} - \Big(\sum_{j\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{E}}}\sum_{q'\in\mathcal{Q}}\phi^{jpq'}_{irq}V^{jpq'}_{irq} + \sum_{j\in\mathcal{N}^C}\sum_{q'\in\mathcal{Q}}\phi^{jpq'}_{ipq}O^{jq'}_{ipq}\Big). \tag{13}$$

Table 2
Nomenclature.

Sets	
$\mathcal{P}$	Set of products, indexed by r, p, e
$\mathcal{P}^{\mathcal{R}}$	Set of resources produced at harvest locations ($\mathcal{P}^{\mathcal{R}} \subset \mathcal{P}$)
$\mathcal{P}^{\mathcal{E}}$	Set of outputs produced at process locations ($\mathcal{P}^{\mathcal{E}} \subset \mathcal{P}$)
$\mathcal{P}^{\mathcal{P}}$	Set of main outputs produced at process locations ($\mathcal{P}^{\mathcal{P}} \subset \mathcal{P}^{\mathcal{E}}$)
$\mathcal{A}$	Set of product categories demanded by customers, indexed by a
$\mathcal{C}_p$	Set of input categories of products required to produce main output p, indexed by c
$\mathcal{E}_p$	Set of outputs that are produced when main output p is produced, indexed by e
$\mathcal{N}^H$	Set of harvest locations, indexed by i, j
$\mathcal{N}^O$	Set of process locations, indexed by i, j
$\mathcal{N}^C$	Set of customer locations, indexed by i, j
$\mathcal{Q}$	Set of quality levels, indexed by q, q', q''
Parameters	
β_{ipq}	Supply of resource p with quality q at location i [kg]
δ^L_{ia}	Demand lower bound for product category a at customer location i [kg]
δ^U_{ia}	Demand upper bound for product category a at customer location i [kg]
Ψ_{iaq}	Returned value of selling product category a with quality q to customer location i [€/kg]
c^T_{ijp}	Costs to transport product p from location i to location j [€/kg]
c^H_{ip}	Costs to harvest resource p at harvest location i [€/kg]
c^U_{ip}	Costs for unused supply of resource p at harvest location i [€/kg]
c^P_{ip}	Costs to produce main output p at process location i [€/kg]
c^S_{ip}	Setup costs for producing main output p at process location i [€]
c^D_p	Costs for disposing product p [€/kg]
θ	Purchasing cost factor indicating the ratio between purchasing and harvesting costs
e^O_{ip}	Exergy input required for the production of output p at process location i [MJ/kg]
e^T_{ijp}	Exergy losses associated with the transport of product p from location i to location j [MJ/kg]
e^P_{ip}	Exergy losses associated with wasting product p at location i [MJ/kg]
ω^O_{ic}	Proportion of waste due to processing products from input category c at process location i [kg/kg]
ω^T_{ijp}	Proportion of waste due to transporting product p from location i to location j [kg/kg]
η^I_{ip}	Maximum processing capacity based on input to process product p at process location i [kg/h]
η^O_{ip}	Maximum production capacity based on output to produce output p at process location i [kg]
ξ_i	Maximum number of working hours available at process location i [h]
γ_{cpq}	Proportion of products from input category c required to produce output p with quality q [kg/kg]
$l^{eq'}_{irpq}$	Proportion of output e with quality q' that is produced when product r is processed into main output p with quality q at process location i [kg/kg]
$\phi^{jpq'}_{irq}$	Parameter that has a value of 1, if product r with quality q from location i can either be processed into or remain as product p of quality q' at location j; 0 otherwise
$\pi^{eq'}_{ipq}$	Parameter that has a value of 1, if output e with quality q' occurs when main output p with quality q is produced at process location i; 0 otherwise
λ_{rcp}	Parameter that has a value of 1, if product r belongs to the products from input category c to produce output p; 0 otherwise
α_{pqaj}	Parameter that has a value of 1, if product p with quality q can be used to satisfy the demand of product category a of customer j; 0 otherwise
Decision variables	
$H^{jq'}_{ipq} \in \mathbb{R}_{\geq}$	Quantity of resource p with quality q from harvest location i that reaches customer location j with quality q' [kg]
$O^{jq'}_{ipq} \in \mathbb{R}_{\geq}$	Quantity of output p with quality q from process location i that reaches customer location j with quality q' [kg]
$Y^{jpq'}_{irq} \in \mathbb{R}_{\geq}$	Supplied quantity of resource r with quality q from harvest location i used for the production of main output p with quality q' at process location j [kg]
$V^{jpq'}_{irq} \in \mathbb{R}_{\geq}$	Supplied quantity of output r with quality q from process location i used for the production of main output p with quality q' at process location j [kg]
$X_{ipq} \in \mathbb{R}_{\geq}$	Production quantity of output p with quality q at process location i [kg]
$Z_{ipq} \in \{0,1\}$	$\begin{cases} 1, & \text{if output } p \text{ with quality } q \text{ is produced at process location } i \\ 0, & \text{otherwise} \end{cases}$
$S_{pqai} \in \{0,1\}$	$\begin{cases} 1, & \text{if the demand for product category } a \text{ at customer location } i \text{ is satisfied by product } p \text{ with quality } q \text{ [kg/kg]} \\ 0, & \text{otherwise} \end{cases}$
$F_{pqaj} \in \mathbb{R}_{\geq}$	Quantity of product p with quality q used to satisfy the demand of product category a of customer i [kg]
$B_{ipq} \in \mathbb{R}_{\geq}$	Purchased quantity of resource p with quality q at location i [kg]
$U^S_{irq} \in \mathbb{R}_{\geq}$	Quantity of unused supply of resource r with quality q at harvest location i [kg]
$U^T_{ipq} \in \mathbb{R}_{\geq}$	Quantity of unused output p with quality q at process location i [kg]
$W^{T^o}_{ip} \in \mathbb{R}_{\geq}$	Quantity of waste occurring due to transporting product p to processing location i [kg]
$W^{T^c}_{ip} \in \mathbb{R}_{\geq}$	Quantity of waste occurring due to transporting product p to customer location i [kg]
$W^P_{ip} \in \mathbb{R}_{\geq}$	Quantity of waste occurring due to producing output p at process location i [kg]

4.2. Key performance indicators

The performance of the studied production system is assessed using two key performance indicators as objectives in our model, namely total profit and total exergy loss.

Total profit

Total profit is chosen as a Key Performance Indicator, maximising the economic performance of the production system. It is calculated as the difference between the revenue (14a) and the total cost associated with harvesting (14b), purchasing (14c), processing (14d), transport (14e), production setup (14f), and disposal (14g).

$$\max \Bigg\{ \sum_{j\in\mathcal{N}^C}\sum_{a\in\mathcal{A}}\sum_{q\in\mathcal{Q}}\sum_{p\in\mathcal{P}^{\mathcal{R}}} \psi_{jaq'} F_{pqaj} \tag{14a}$$

$$- \sum_{i\in\mathcal{N}^H}\sum_{q,q'\in\mathcal{Q}} \Big(\sum_{j\in\mathcal{N}^C}\sum_{p\in\mathcal{P}^{\mathcal{R}}} c^H_{ip} H^{jq'}_{ipq} + \sum_{j\in\mathcal{N}^O}\sum_{r,p\in\mathcal{P}} c^H_{ip} Y^{jpq'}_{irq}$$

$$+ \sum_{i\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{E}}}\sum_{q\in\mathcal{Q}} c^U_{ip} U^T_{ipq} \Big) \tag{14b}$$

$$- \sum_{i\in\mathcal{N}^H}\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}} \theta c^H_{ip} B_{ipq} \tag{14c}$$

$$- \sum_{i\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{P}}}\sum_{q\in\mathcal{Q}} c^P_{ip} X_{ipq} \tag{14d}$$

$$- \sum_{p\in\mathcal{P}}\sum_{q,q'\in\mathcal{Q}} \Big(\sum_{i\in\mathcal{N}^H}\sum_{j\in\mathcal{N}^C} c^T_{ijp} H^{jq'}_{ipq} + \sum_{i\in\mathcal{N}^O}\sum_{j\in\mathcal{N}^C} c^T_{ijp} O^{jq'}_{ipq}$$

$$+ \sum_{i\in\mathcal{N}^H}\sum_{j\in\mathcal{N}^O}\sum_{r\in\mathcal{P}} c^T_{ijp} Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O}\sum_{j\in\mathcal{N}^O}\sum_{r\in\mathcal{P}} c^T_{ijp} V^{jpq'}_{irq} \Big) \tag{14e}$$

$$- \sum_{i\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{P}}}\sum_{q\in\mathcal{Q}} c^S_{ip} Z_{ipq} \tag{14f}$$

$$- \Big(\sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{N}^O} c^D_p W^{T^o}_{ip} + \sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{N}^C} c^D_p W^{T^c}_{ip} + \sum_{i\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{E}}} c^D_p W^P_{ip}$$

$$+ \sum_{i\in\mathcal{N}^H}\sum_{p\in\mathcal{P}^{\mathcal{R}}}\sum_{q\in\mathcal{Q}} c^D_p U^S_{ipq} + \sum_{i\in\mathcal{N}^O}\sum_{p\in\mathcal{P}^{\mathcal{E}}}\sum_{q\in\mathcal{Q}} c^D_p U^T_{ipq} \Big) \Bigg\} \tag{14g}$$

Total exergy loss

Total exergy loss is chosen as a second key performance indicator, minimising the environmental impact of the production system. Exergy is based on the basic concepts of thermodynamics, measuring the amount of work, i.e., the energy (expressed in Joules) that can be extracted from a product (Apaiah et al., 2006). Exergy losses occur when a product is wasted as every product contains exergy (mainly chemical exergy), so that if a product is not reused and becomes waste, the exergetic value of the product is considered a loss (Banasik et al., 2017a). In addition, exergy losses also occur during most activities, as exergy is not conserved, i.e., the exergy input of a process is generally higher than its output (Apaiah et al., 2006). We, thus, minimise total exergy losses related to product waste (15a) as well as the losses resulting from transport (15b) and processing (15c) activities (see Eq. (15a)–Eq. (15c) in Box I).

5. Experimental design

We conduct a numerical analysis considering a real-life case study to test our model and gain valuable practical insights. In this context, we first present the basic case setting, which we refer to as the *Base Case*, before discussing several other scenarios and case settings that allow us to explore different features of the problem in more detail, thus enriching our analysis.

5.1. Base case

The real-life case study presented in this research is based on the carrot-processing operations of a Dutch vegetable processor, using various carrot varieties to create different-sized carrot products, including peeled, cut, and scraped carrots, as well as small snack carrots and carrot balls. In this context, product quality is assessed based on carrot size. Aiming to reduce waste throughout the chain, the carrot processor seeks to determine its optimal weekly production decisions at the processing facilities considering product-specific recipes, including the reusability of certain outputs (such as side and waste streams) as production inputs for other processes. We collected supply, recipe, cost, and demand data from the dataset of the carrot processor of 2022 to create this case. Since our model is supply-driven, we aim to investigate how variations in supply quantities influence outcomes. To achieve this, we selected two supply scenarios based on recommendations from the Dutch vegetable processor, namely one week with low-supply (LS) and another with high-supply (HS) quantities. The first represents low supply weeks typical of autumn, winter, and spring, while the second reflects high supply weeks, approximately ten times greater, typical of the summer harvest season. These scenarios capture the stark contrast between harvest periods and off-seasons, enabling a clearer analysis of supply dynamics.

The supply data is based on a single storage centre, which we consider as the 'harvest location' due to the lack of specific harvest location data within our case study. From this harvest location, 17 types of resources $\mathcal{P}^{\mathcal{R}}$ are allocated to 6 nearby processing lines $\mathcal{N}^O$, where they can be processed into 231 various-sized outputs $\mathcal{P}^{\mathcal{E}}$, of which 63 are considered main outputs $\mathcal{P}^{\mathcal{P}}$. In the case of the LS week (HS week), the processor uses these outputs to serve 32 (34) customers $\mathcal{N}^C$ who have a flexible demand for 98 (101) product categories $\mathcal{A}$. This demand flexibility implies that although the sold quantity for a given product needs to be satisfied by a single product type from that category, this quantity may vary within a specified range (see Assumption 4). The lower bound of this range is based on the available data. However, to make the network more flexible and less demand-driven, we set the upper bound at 110% to accommodate potential side streams. Using such a range is reasonable from a practical perspective, as supply and demand fluctuations are inherent to these supply chains, and customers generally accept some level of flexibility.

Product-specific revenues, as well as harvesting and processing costs, are provided by the processor. The purchasing costs are assumed to be slightly higher than the harvesting costs yet follow a similar trend, so we apply a cost factor θ of 1.1, making the purchasing costs dependent on the harvesting costs (see Assumption 1). Transportation costs are already included in the purchasing and harvesting costs, as in the context of our case study, transportation falls outside the processor's responsibility. Within the setting of the *Base Case*, the processing locations represent pre-existing production lines that are used daily so that the decision to open a specific process location Z and the corresponding setup costs are not considered.

As no exergy data was directly available from the processor, the exergy values used are based on data obtained from the literature. Moreover, in terms of the exergy input required for processing, we only consider electrical exergy to be relevant, which we base on the company's energy data. The intrinsic exergy of resources and products, on the other hand, has been determined based on the nutritional value of carrots (see Table A.6) in combination with the standard chemical exergy of the nutritional components (as referenced in Table A.5).

This case setting, which we refer to as the *Base Case*, serves as a benchmark for the other scenarios and case settings and forms the basis of our comparative analysis. An overview of the data sources used can be found in Table A.4.

$$\min \left\{ \sum_{p\in\mathcal{P}} \sum_{i\in\mathcal{N}^O} e^P_{ip} W^{T^o}_{ip} + \sum_{p\in\mathcal{P}} \sum_{i\in\mathcal{N}^C} e^P_{ip} W^{T^c}_{ip} + \sum_{i\in\mathcal{N}^O} \sum_{p\in\mathcal{P}^\mathcal{E}} e^P_{ip} W^P_{ip} + \sum_{i\in\mathcal{N}^H} \sum_{p\in\mathcal{P}^\mathcal{R}} \sum_{q\in\mathcal{Q}} e^P_{ip} U^S_{ipq} + \sum_{i\in\mathcal{N}^O} \sum_{p\in\mathcal{P}^\mathcal{E}} \sum_{q\in\mathcal{Q}} e^P_{ip} U^T_{ipq} \right. \tag{15a}$$

$$+ \sum_{p\in\mathcal{P}} \sum_{q,q'\in\mathcal{Q}} \left(\sum_{i\in\mathcal{N}^H} \sum_{j\in\mathcal{N}^C} e^T_{ijp} H^{jq'}_{ipq} + \sum_{i\in\mathcal{N}^O} \sum_{j\in\mathcal{N}^C} e^T_{ijp} O^{jq'}_{ipq} + \sum_{i\in\mathcal{N}^H} \sum_{j\in\mathcal{N}^O} \sum_{r\in\mathcal{P}} e^T_{ijp} Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O} \sum_{j\in\mathcal{N}^O} \sum_{r\in\mathcal{P}} e^T_{ijp} V^{jpq'}_{irq} \right) \tag{15b}$$

$$+ \underbrace{\sum_{j\in\mathcal{N}^O} \sum_{r,p\in\mathcal{P}} \sum_{c\in C_p} \sum_{q,q'\in\mathcal{Q}} e^P_{jr} \left(1-\omega^O_{jc}\right) \left(\sum_{i\in\mathcal{N}^H} \left(1-\omega^T_{ijr}\right) Y^{jpq'}_{irq} + \sum_{i\in\mathcal{N}^O} \left(1-\omega^T_{ijr}\right) V^{jpq'}_{irq} \right)}_{\textbf{intrinsic input exergy}}$$

$$\left. + \underbrace{\sum_{j\in\mathcal{N}^O} \sum_{p\in\mathcal{P}^\mathcal{E}} \sum_{q\in\mathcal{Q}} \left(e^O_{jp} - e^P_{jp}\right) X_{jpq}}_{\textbf{processing - intrinsic output exergy}} \right\} \tag{15c}$$

Box I.

Table 3
Parameter setting for the scenarios.

Scenarios	Parameter	List of percentages used (%)
Cost	c^H	50, 150, 200, 250, 300
	c^P	50, 150, 200, 250, 300
Processing waste	ω^O	25, 50, 75, 125, 150
Exergy loss	e^P	50, 150, 200, 250, 300
	e^O	25, 50, 200, 400
Demand	δ^L	25, 50, 75
	δ^U	125, 150, 175

5.2. Scenarios

Altering the values of certain parameters from the *Base Case* setting, we consider several specific scenarios to study the impact of different aspects on the solutions obtained. A detailed description of these scenarios is provided below, while Table 3 presents an overview of the considered parameter ranges for each scenario (given in percentages relative to the *Base Case*).

- **Cost Scenarios:** Given the variability in harvesting costs c^H within practical contexts and the potential impact this may have on the economic viability of waste valorisation, we carry out a set of experiments to investigate the effect of harvesting cost fluctuations. In this context, it should be noted that harvesting cost fluctuations also affect the purchasing costs as these are assumed to be dependent. To study variations in the purchasing costs that occur independently from changes in the harvesting costs, e.g., triggered by a change in suppliers, we consider a separate scenario altering solely the purchasing cost factor θ, using values of 1.05, 1.2, 1.3, 1.4, and 1.5, while the harvesting costs remain unchanged. Moreover, we explore the effect of different processing cost values c^P, considering that the introduction of additional side-stream-based products generally goes hand in hand with the introduction of new processes, for which processing costs are not yet known, which may impact the economic viability of waste valorisation.
- **Processing Waste Scenarios:** As processing efficiency may vary among companies and processing equipment, we aim, furthermore, to analyse the effect of using slightly more or less efficient processes by varying the waste percentages ω^O during processing, while recognising that this percentage is unlikely to experience drastic changes.
- **Exergy Loss Scenarios:** Given the differences in intrinsic exergy among food products, and the potential effect this may have on the environmental impact of waste valorisation, we aim to understand the potential effects of processing other products by varying the intrinsic exergy values e^P, thus generalising our findings to other settings than the case of the Dutch carrot processor. Furthermore, to test the effect of using processes with different exergy values, we alter the processing exergies e^O.
- **Demand Scenarios:** To analyse the impact of having a more flexible demand and, thus, a less demand-driven supply chain, we conduct experiments varying the demand lower δ^L and upper bounds δ^U.

5.3. Case settings

Slightly altering the problem setting from the *Base Case*, we furthermore consider two additional case settings to study the impact of alternative problem settings on the solutions obtained.

- **Mixing - Case Setting:** In this case setting, we examine the economic and environmental implications of allowing to fulfil the customer demand for a product category by mixing different products from that category. In this setting, the decision variable S_{pqai} is defined as a continuous variable, indicating the proportion of the demand of a product category satisfied by a certain product. To ensure that customer demand for product categories can only be satisfied by the products within this category, we then introduce Constraints (16), which hold for all products $p \in \mathcal{P}$, all qualities $q \in \mathcal{Q}$, all customer locations $j \in \mathcal{N}^C$, and all product categories $a \in \mathcal{A}$.

$$F_{pqaj} \leq \alpha_{pqaj} \delta^U_{ja}, \tag{16}$$

while simultaneously omitting constraints (6), (7), and (8).
- **Portfolio Extension - Case Setting:** Considering a possible extension of the product portfolio and thus a broader spectrum of side-stream categories and related processing options, this setting explores the potential of additional valorisation options for the carrot processor. For this purpose, we extend the product set with fourteen side-stream-based product categories, including side streams from processing lines, such as carrot heads, peels, and scrapes, as well as the harvest side stream carrot leaves (0.874 g/g carrot root, based on van Ravestijn (1986)) as inputs. The considered product categories can, then, be classified into two categories: core carrot product categories (corresponding to the initial product categories used in the *Base Case*), which are characterised by a relatively fixed demand, and side-stream-based product categories, with a more flexible demand (between 0 and 80% of the average demand for core carrot products).
In comparison to the *Base Case*, this results in a case setting with 12 additional processing lines $\mathcal{N}^O$, 1 additional resource

$\mathcal{P}^{\mathcal{R}}$, and 104 outputs $\mathcal{P}^{\mathcal{E}}$, all of which are main outputs $\mathcal{P}^{\mathcal{P}}$. The recipes for the side-stream-based products are derived from currently available supermarket products, and we expect that additional required ingredients can be readily supplied. Assuming that the processor is only responsible for the processing of carrot ingredients, we simplify our calculations by only considering the costs and revenues attributed to the carrot fraction of these products using the average processing cost and revenue of core carrot products (see Table A.7). Moreover, in contrast to the core carrot product lines, for which setup costs are not considered as explained in Section 5.1, we do include setup costs for the processing lines of side-stream-based products, as these lines are not part of the pre-existing, daily operations and may require additional setup costs. The data regarding the processing lines' setup costs are based on Duarte et al. (2021), and the electrical energy input for the side-stream-based products is taken from the literature (see Table A.8). The intrinsic exergy of carrot leaves is assumed to be comparable to that of sugar beet leaves, as reported by Tenorio et al. (2017). An overview of the additional data sources used for the side-stream-based products can be found in Table A.4.

6. Results

This section presents the results of our model, optimising the different scenarios and case settings for both the low-supply (LS) and high-supply (HS) weeks under consideration of the two objectives. Based on these results, we evaluate the system's performance, measuring and comparing cost and exergy losses as well as the input and output quantities within the system. In this context, Section 6.1 first presents the results for the *Base Case* before investigating the trade-off between the considered objectives based on a Pareto frontier in Section 6.1.1. Analysing the effects of variations in costs, waste fractions, exergy losses, and demand flexibility, the results for the different scenarios are then presented in Section 6.2, while the results for the altered case settings, exploring the potential of product mixing and a portfolio extension, follow in Section 6.3. For confidentiality reasons, we removed the scale in all the figures and did not display the actual values. Computationally, all experiments are performed in Julia, version 1.8.2-linux-x86_64, and solved with Gurobi, version 10.0.1-GCCcore-11.3.0.

6.1. Base case

Examining the results for the LS and HS weeks for both objectives in Fig. 2, we observe from Fig. 2(a) that the total profit in the LS week is higher, whereas Fig. 2(b) shows that exergy losses are significantly lower that week. These differences in objective values for the LS and HS week indicate that the quantity supplied significantly impacts the profitability as well as the environmental impact of the system. Looking at the solution structure in more detail, Fig. 3(b) shows that when maximising profit (minimising exergy losses), process side streams, in the form of unused output exergy losses, account for 50 (55)% of the total exergy losses in the LS week and 31 (31)% in the HS week. Harvest side streams, on the other hand, represented by unused supply exergy losses, contribute 33 (38)% of the total exergy losses in the HS week while the exergy contribution of harvest side streams in the LS week is minimal.

Comparing the minimisation of exergy losses with the maximisation of total profit for the two weeks, we observe in Fig. 2 that significant trade-offs exist between the two objectives. Analysing the different components of the solutions in greater detail, we observe from Fig. 3 that the reductions in exergy losses when exergy losses are minimised stem predominantly from a decrease in exergy losses from processing and, to a lesser extent, from a reduction of the exergy losses from unused output and processing waste (Fig. 3(b)), due to a reduction in the waste quantities (as shown in Fig. 3(c)). Studying the obtained solutions in more detail, these reductions in exergy losses and waste can be attributed to a shift towards processes with lower exergy losses and waste fractions (e.g., cutting, sorting, and robot lines). This strategic shift in process operations is mainly achieved by purchasing more expensive resources (Fig. 3(a)), which require less or less wasteful processing to be transformed into comparable output quantities, thus resulting in a lower input-to-output ratio. This is in line with the significant reductions in purchasing, total output, and reuse quantities (shown in Fig. 3(d)), which go beyond what would be expected from the slight decrease in sales alone. Therefore, to obtain a more environmentally friendly product portfolio, it is preferred to focus on more efficient purchasing strategies and less impactful processing configurations rather than reducing waste through more reuse and side-stream valorisation. The most profitable product portfolio, on the other hand, minimises costs by purchasing the least expensive resources, which require additional processing steps to create a saleable output and, in turn, encourage more reuse. The small discrepancy in the unused supply quantity for both objectives and both weeks suggests, moreover, that other factors constrain reuse and supply valorisation, rendering certain resources ineffective in the system.

Thus, achieving an optimal balance between profit maximisation and minimisation of exergy losses requires navigating a complex trade-off between cost-effective purchasing and waste-reducing processing strategies.

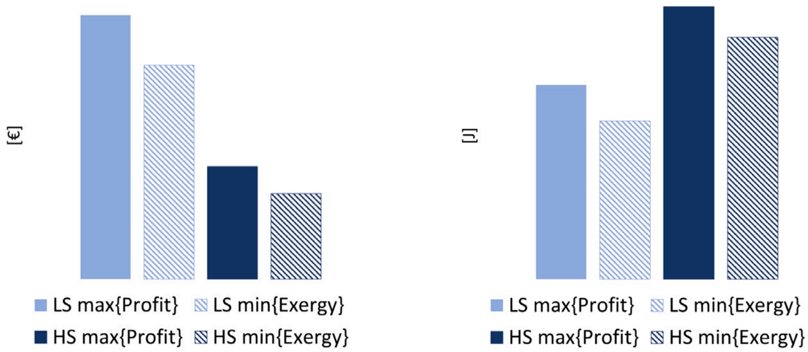
6.1.1. Trade-off between objectives

To investigate the trade-off between the two objectives in more detail, we performed a Pareto analysis for the *Base Case*, using the ϵ-constraint method (as described in Chapter 4 of Ehrgott (2005)). For this analysis, the efficient solutions are calculated by maximising the total profit objective, while the exergy loss objective is used as a constraint. This process is repeated for different ranges obtained from a sensitivity analysis with regard to the right-hand side of the constraint. Fig. 4 shows, in this context, the resulting set of efficient solutions, while Table B.9 enables the evaluation of the Pareto-efficient solutions in more detail. Two distinctive kinks in the trade-off curves can be identified from this figure for both the LS and the HS week, dividing the curves into three line sections. The results indicate that an initial decrease in exergy (of about 3%) can be achieved relatively easily without resulting in a big reduction in profit (only 0.5%). The subsequent change in the slope of the trade-off curve suggests, however, that beyond this point a decrease in exergy comes at a higher cost. This effect is even more pronounced in the case of the HS week.

Looking at the underlying solution structure, these observed kinks can be mainly attributed to changes in sales quantities, which decrease linearly in the first sections, remain relatively stable in the second, and then decrease again in the third sections, while the product portfolio remains relatively similar. The changes along the line sections, on the other hand, can be attributed to reductions in purchasing, total output, and reuse quantities, which is in line with our observations in Section 6.1. The practical implication for stakeholders is that a balanced approach, prioritising moderate exergy loss reductions without extreme profit decreases, could offer the most sustainable path. Industries that prioritise environmental goals, however, might need to invest more in energy-efficient processes or tailored resources.

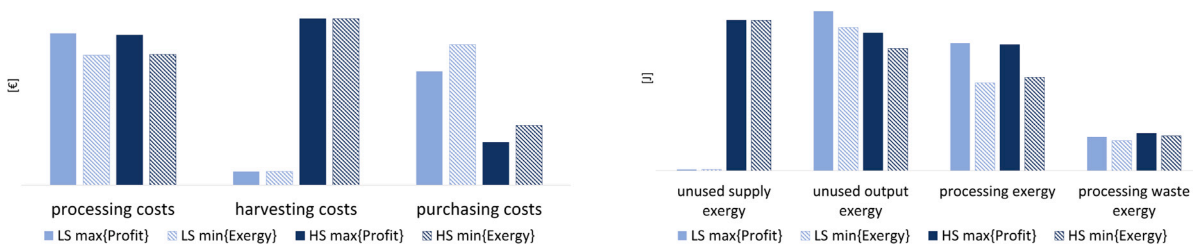
6.2. Scenarios

Investigating the effect of variations in different cost components, processing waste fractions, and the considered exergy loss data, as well as the impact of a less demand-driven supply chain, this section presents the results of the scenarios described in Section 5.2. Figs. 5 and 6 depict these results in percentages relative to when the model was optimised for the same objective using the parameter values of the Base Case (i.e., set to 100%). Given that the LS and HS week results

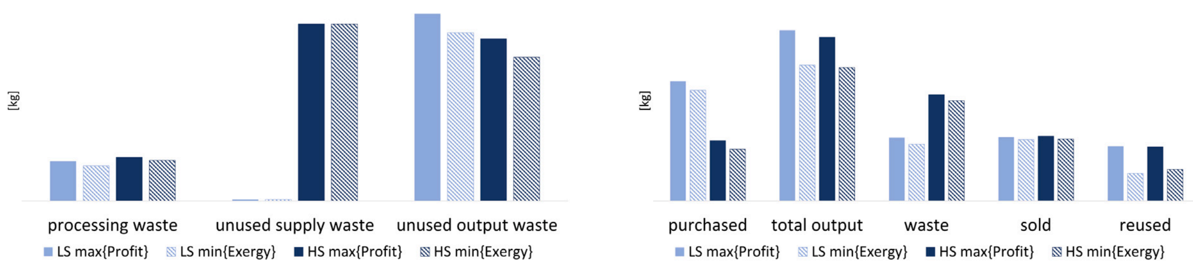


(a) Total profit (b) Exergy losses

Fig. 2. Values corresponding to the solutions of the *Base Case*, optimising for the total profit (max{Profit}) and exergy loss (min{Exergy}) objective.



(a) Cost components (b) Types of exergy losses



(c) Waste components (d) Product flows

Fig. 3. Values corresponding to the solutions of the *Base Case*, optimising for the total profit (max{Profit}) and exergy loss (min{Exergy}) objective.

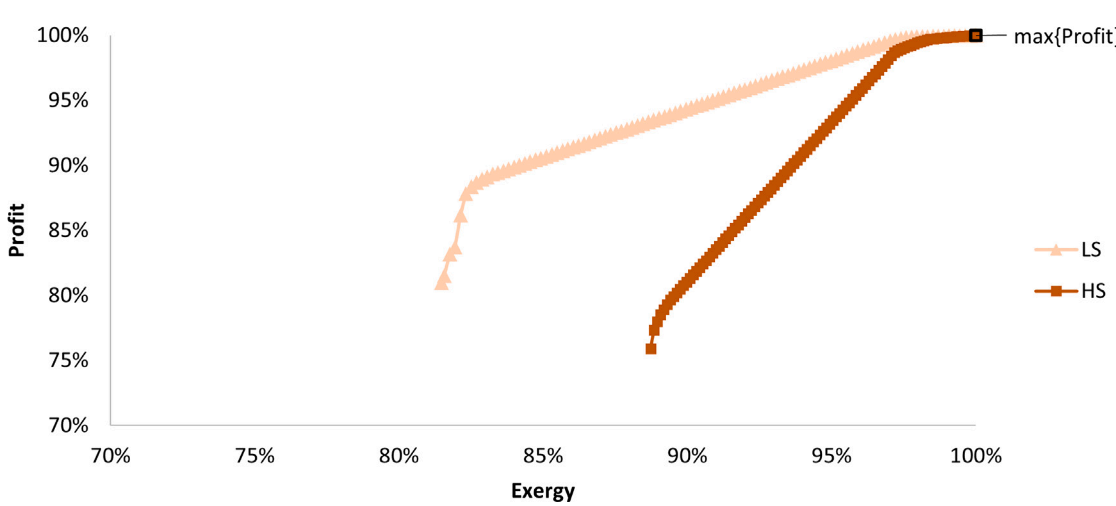


Fig. 4. Pareto curves for the LS and HS week, with the values of the efficient solutions shown in comparison to the max{Profit} solution (=100%).

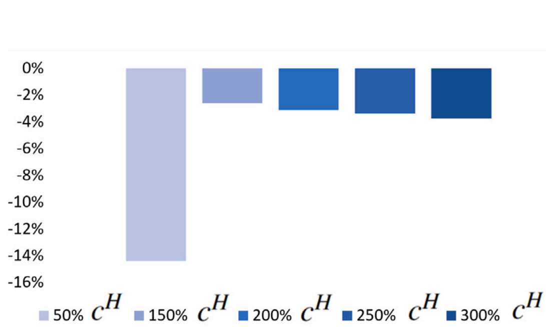
are very similar, this section only discusses the results for the LS week. All solution values for both the LS and the HS week are provided in Appendix: Tables B.10 & B.11.

- **Cost Scenarios:** Focusing on the impact of harvesting cost fluctuations, we see different results for lower and higher harvesting costs. Looking at lower harvesting costs first, we observe that profit increases for both objectives. However, exergy losses only decrease in comparison to the *Base Case* when total profit is maximised (Fig. 5(a)), and remain unchanged when exergy losses are minimised as the solution structure remains unchanged. Focusing on changes in the product flows for the case when profit is maximised, we observe for both objectives (as illustrated in Fig. 5(b)) that purchasing, total output, waste, and particularly reuse quantities decrease significantly, while sold quantities remain similar. This suggests that when resources are more affordable, there is a tendency to purchase (relatively more expensive) resources with a lower input–output ratio which, for example, require fewer processing steps, similar to the trend observed for the *Base Case* when exergy losses are minimised. In the context of higher harvesting costs, profit tends to decrease as harvesting costs increase for both objectives. Exergy losses, on the other hand, only decrease slightly when total profit is maximised (Fig. 5(a)) and remain unchanged when exergy losses are minimised. Looking more closely at the solution structure, when profit is maximised, we observe a reduction in the quantities sold as well as in the purchasing, total output, waste, and reuse quantities. This is a result of the supply-driven nature as well as the dependency between purchasing and harvesting costs (Assumption 1), which leads to a significant increase in the total costs, diminishing the revenues and thus prompting a strategic shift towards only selling the minimum required quantities.
  Focusing on the effect of fluctuations in purchasing costs that are independent of the harvesting costs, we obtain similar findings for total profit and exergy loss values as well as for the in- and output quantities as in the case of higher harvesting costs (Appendix: Table B.10 & B.11).
  Investigating the effect of processing cost fluctuations, we observe that higher processing costs lead in both supply weeks to overall lower profits independently of the considered objective, as well as lower purchase, total output, waste, sold, and reuse quantities when profit is maximised (Fig. 6(a)), which aligns with the results observed for other cost increases. In contrast, unused supply waste (Fig. 6(b)) and associated exergy losses show a sudden increase with increasing processing costs when optimising for total profit, likely triggered by the purchase of resources that need less processing instead of using the available supply which would require more processing. Thus, high processing costs in contrast to high harvesting/purchasing costs seem to discourage supply valorisation. Moreover, interestingly, increasing the processing costs slightly (to 150%) seems to have a bigger effect on product flows than further increases (up to 300%), suggesting a tipping point where further cost increases do not change the optimal solution much.
- **Processing Waste Scenarios:** Comparing the impact of various processing waste fractions, we observe for both objectives that as waste fractions increase, profit decreases whereas exergy losses increase (Appendix: Table B.10 & B.11). Simultaneously, we observe that unused supply waste decreases, whereas unused output and processing waste increase, which is in line with expectations as more waste occurs during processing.
- **Exergy Loss Scenarios:** Studying the effect of different product and processing exergy losses, we obtain comparable findings for both exergy loss fluctuations. In this context, exergy losses increase with higher product and processing exergy losses, while total profit is only affected when minimising exergy losses. Nonetheless, the solution structure is hardly impacted (Appendix: Figs. B.10 and B.11). These insights suggest that there is barely any trade-off between minimising product or processing exergy losses, as a reduction in exergy losses generally seems to go hand in hand with a reduction in production.
- **Demand Scenarios:** To assess the impact of more flexibility in the demand, we test scenarios with a lower minimum required demand as well as scenarios where the maximum permitted demand is increased. The results of these scenarios (Appendix: Table B.10 & B.11) indicate that reducing the lower bound for demand fulfilment or increasing the demand upper bound provides the model with more flexibility when optimising the product portfolio for a given objective. As a result, the model dedicates the available resources to the processing options that are most in line with the considered objective, which may come at the expense of the other objective. At the same time, we observe that reducing the demand lower bound reduces waste for both objectives, as unused output and processing waste decrease with the reduction in total output quantities triggered by the lower sales quantities. In contrast, an increase in the demand upper bound leads to an increase in waste when maximising total profit and a decrease when minimising exergy loss. At the same time, we observe that unused supply waste decreases for both objectives, as more of the supplied resources can be used to fulfil demand. From a valorisation perspective, this indicates that a less demand-driven supply chain promotes supply valorisation, and that further supply valorisation in the *Base Case* was restricted by the more limited demand. However, when maximising total profit, this reduction in unused supply waste is offset by increased processing and unused output waste, resulting from higher purchasing quantities aimed at boosting sales.

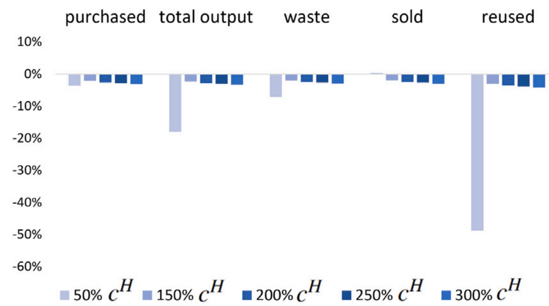
6.3. Case settings

In this section, we analyse the potential of product mixing for demand fulfilment as well as a portfolio extension with side-stream-based products, considering the case settings presented in Section 5.3, and comparing these results to the *Base Case* results.

- **Mixing - Case Setting**: Comparing the solutions of the *Mixing - Case Setting* with the ones of the *Base Case*, we observe that mixing generally has a slight positive effect on total profit, except in the case of the HS week when exergy is minimised. On the other hand, the effect on exergy loss is always positive, with the extent of the reduction varying depending on the considered objective and week. The smallest decrease in exergy can be observed in this context for the case of the HS week when profit is optimised while the biggest reduction is achieved for the LS week when exergy is minimised. The changes in exergy in the high-supply scenarios can mostly be attributed to a reduction in unused supply exergy losses as a result of product mixing, which permits combining different products and resources to fulfil the demand of a category. Thus, supplied resources, which were leftover in other settings due to insufficient quantities, now do no longer remain unused, indicating that supply valorisation is the main strategy when minimising environmental impact in high-supply situations where product mixing is allowed. In low-supply scenarios, on the other hand, the changes are primarily a result of using leftover outputs from other processing lines, suggesting that side-stream valorisation is the main strategy in these situations.
- **Portfolio Extension - Case Setting**:
  Comparing the solutions for the *Portfolio Extension - Case Setting* with the *Base Case*, we observe from Fig. 7 that the positive effect on total profits in the case of a portfolio extension is even greater than in the *Mixing - Case Setting* due to the introduction of new

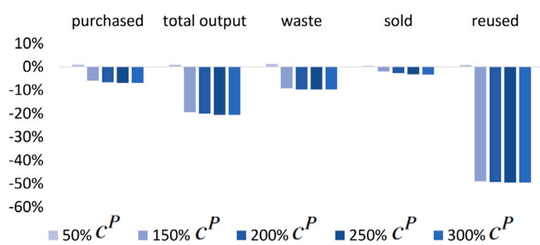


(a) Exergy losses

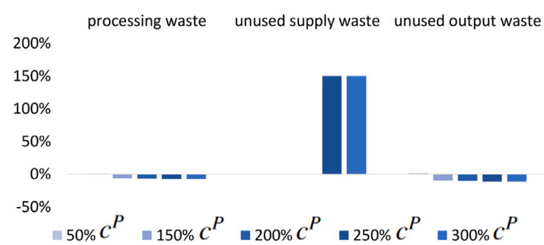


(b) Product flows

Fig. 5. Values corresponding to the solutions of the different harvesting costs c^H (in % to the *Base Case* values), optimising for the total profit (max{Profit}) objective in the LS week.



(a) Product flows



(b) Waste components

Fig. 6. Values corresponding to the solutions of the different processing costs c^P (in % to the *Base Case* values), optimising for the total profit (max{Profit}) objective in the LS week.

side-stream based products (Fig. 8). The small increase in the total costs resulting from the processing of these new products is, as such, compensated by the additional revenues obtained from the sale of these products. Maximising total profit, we furthermore observe a reduction in the purchasing costs, which suggests that side-stream valorisation can replace the purchase of additional resources, making it a profitable strategy depending on the considered product portfolio. Focusing on the performance in terms of exergy losses, we observe similar trends again as in the *Mixing - Case Setting*, with Fig. 7(b) showcasing a general decrease in the observed exergy losses due to a reduction in unused output exergy losses as the process side streams can now be used as ingredients for the side-stream-based products. However, these changes are less pronounced than in the *Mixing - Case Setting*, which can be explained by the fact that the production of additional (side-stream-based) products (Fig. 9) requires additional processing which in turn leads to higher (waste) exergy losses. The portfolio extension is as such smaller when exergy losses are minimised, focusing predominantly on products with low processing exergy, such as carrot juice or carrot top soup.

7. Discussion

The results of this study reveal that side-stream valorisation is often well aligned with the objective of profit maximisation. Our findings also indicate that expanding the product portfolio (as explored in RQ 5), including both process- and harvest-side-stream-based products, can further enhance profitability and increase sale quantities. Farmers, too, stand to benefit financially, as a greater share of their produce can be processed, which could lead to more stable incomes that do not depend so much on the quality of their produce. While multiple studies (Thorsen et al., 2024; Lehn and Schmidt, 2023) confirm that food waste valorisation is generally profitable, they emphasise the need for scaling up and cross-sector collaboration, as well as investments and support from governmental organisations, to ensure long-term viability. Moreover, not all valorisation applications in business contexts are economically beneficial, as additional processing costs may outweigh the financial gains (Heydari, 2024). Furthermore, the economic viability of integrating side-stream products depends on the costs of setup and processing, which may be too high for smaller firms. The model's sensitivity analysis across various scenarios also shows that higher costs and processing waste fractions can significantly reduce profitability (as explored in RQ 6). Thus, a key managerial takeaway is that firms should closely monitor cost fluctuations and processing efficiency to ensure sustainable resource utilisation.

Selling side streams to facilities that can use them as ingredient substitutes may offer a more cost-effective alternative to building new processing lines (Assumption 2), as carrot side streams can replace common ingredients. For example, carrot side streams can partially replace flour in products like wraps and crackers, and carrot syrup can substitute sugar in many products. In this context, it should also be noted that incorporating harvest-side-stream-based products into the product portfolio may require additional investments, e.g., to retrieve these resources from the field. Take, for instance, the case of harvesting cauliflower leaves, which might demand additional labour and transportation expenses since cauliflowers are traditionally hand-harvested. However, there are possibilities for adaptation, such as modifying harvesting machines, as demonstrated in Vervisch (2014). Future research could, thus, extend this analysis by incorporating the harvesting operations and the environmental impacts occurring at the farm level into the framework of this research, to further explore the potential of valorising harvest side streams.

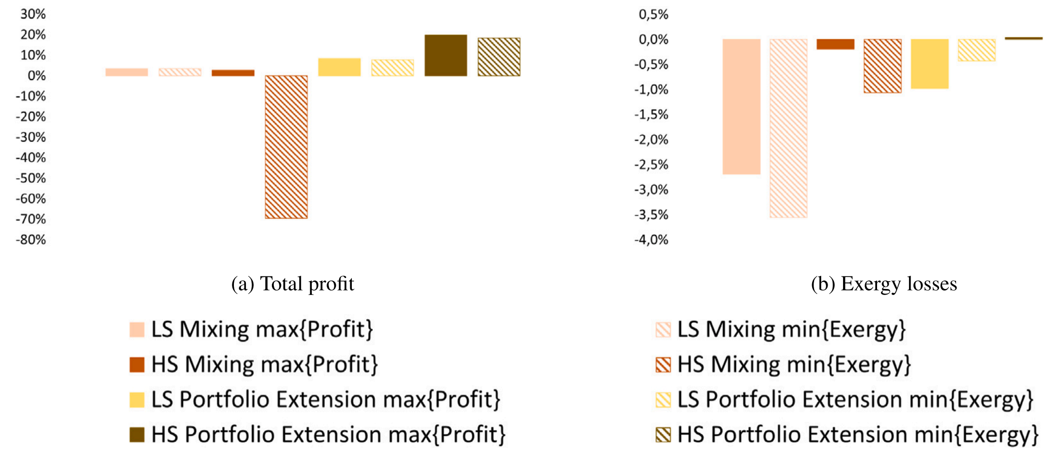


Fig. 7. Objective values corresponding to the case settings (in % to the *Base Case* values), optimising for the total profit (max{Profit}) and exergy loss (min{Exergy}) objective in the LS and HS week.

Fig. 8. Revenue and costs of the *Portfolio Extension - Case Setting* (in % to the *Base Case* values), optimising for the total profit (max{Profit}) and exergy loss (min{Exergy}) objective in the LS and HS week.

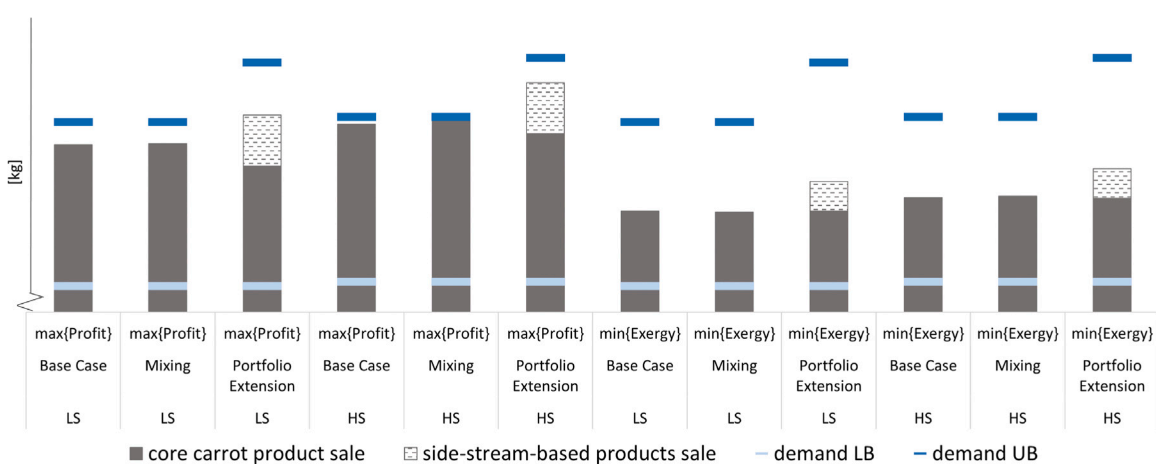


Fig. 9. Sales of different product types of the case settings, optimising for the total profit (max{Profit}) and exergy loss (min{Exergy}) objective in the LS and HS week.

In contrast to profit, the minimisation of environmental impact in the form of exergy loss seems to be generally less compatible with food valorisation (as explored in RQ 3). The latter can be explained by the associated need for additional, more exergy-intensive, processing, which outweighs the gains in terms of environmental impact that can be achieved from the reduction of unused side streams and corresponding waste. This result challenges the widely accepted food waste hierarchy proposed by Papargyropoulou et al. (2014) and refined by Garcia-Garcia et al. (2017), which prioritises conversion to human food as one of the most sustainable interventions. Similar concerns have been raised by Parsa et al. (2023), Thorsen et al. (2024) and Wei et al. (2024), who argue that the hierarchy oversimplifies the complex sustainability trade-offs associated with food valorisation.

Our results further support the argument of Teigiserova et al. (2020) that the environmental benefits of valorisation are highly product- and process-dependent. Through a synthesis of multiple studies, they concluded that valorising high-impact products (e.g., high energy and low water content (Eriksson et al., 2015)) such as beef, yields greater environmental benefits than low-impact products like vegetables, which may explain why our case study on carrots showed limited environmental gains. Similarly, Scherhaufer et al. (2020) found that valorising apple pomace to food ingredients is only beneficial if the processing emissions remain lower than those of the substituted products, suggesting that the environmental benefits of valorisation depend not only on the product but also on the processing method used.

Although in some cases, food valorisation has positive net environmental benefits by avoiding the environmental impacts of substituted and valorised ingredients (Lehn and Schmidt, 2023; Coelho et al., 2023; Eriksson et al., 2021), others highlight that high-energy processes such as drying can offset these gains (Thorsen et al., 2024; Scherhaufer et al., 2020). For instance, Eriksson et al. (2021) show that slicing instead of drying broccoli side streams results in lower environmental impacts across multiple indicators. This matches our findings, as a key implication of our study is that reducing exergy loss requires resource-efficient, low-energy processing. Our findings are consistent with Zisopoulos et al. (2015), who emphasised that optimising process efficiency is essential for reducing exergy losses in food manufacturing. To further mitigate climate change, processors should ensure that transforming side streams into products only occurs when the additional environmental impacts remain lower than the savings from waste reduction. In this regard, investment in research and development aimed at improving the energy efficiency of processing lines and reducing processing waste is crucial. Additionally, shifting to recipes with lower input–output ratios by using more suitable resources that generate less waste during processing can also help minimise environmental impacts. This suggests that refining harvest plans in close collaboration with agricultural suppliers, in order to receive more appropriate resources, could present a promising strategy to reduce the environmental impact of processing and waste.

Aside from environmental benefits, valorising side-streams for ingredient substitution provides additional (functional) benefits, such as allergen reduction, allowing businesses to cater to a wider range of dietary needs. Moreover, side-stream-based products can serve as sustainable alternatives to conventional ingredients while maintaining similar functionality, for instance by replacing animal-based stabilisers with side-stream based equivalents. However, their irregular availability may require retailers to adopt flexible inventory strategies, treating them as seasonal or limited-edition items. Future research should thus establish systematic guidelines for food valorisation, focusing on ingredient and process selection while evaluating substitution effects, such as changes in ingredient functionality, to optimise both economic feasibility and environmental sustainability.

Additionally, our findings show that promoting more flexibility in the demand and thus reducing the demand-driven nature of food supply chains (e.g., through more flexible quantities or product mixing) provides another promising avenue to mitigate the negative effects on the environment, while simultaneously increasing profitability as the available supply can be better utilised (as explored in RQ 4). However, given the established structures and existing dynamics in agri-food chains, processors, as well as agricultural producers, are often faced with little flexibility from the demand side. Similar challenges were noted by Yetkin Özbük and Coşkun (2020), who found that effective food waste reduction requires coordination across the supply chain. A practical implementation of enhanced flexibility (Assumption 4) would thus require significant changes on the demand side in the form of contract adjustments as well as a more general rethinking of our consumption, attitude, and purchasing behaviour, e.g., towards accepting more seasonal products of varying quality standards. Retailers could, for example, adjust their product portfolios by using more general and thus flexible descriptions of their own products (e.g. "vegetable box" instead of specifying individual vegetables), or introducing "surprise" boxes similar to initiatives like Too Good To Go.

8. Conclusions

Investigating the potential of food valorisation from both an economic and environmental perspective, our work offers contributions from both a theoretical as well as a practical perspective.

Through the development of a novel optimisation model that integrates flexible recipes and accommodates various quality dynamics, this research fills several notable gaps in the literature on food waste minimisation and supply chain optimisation, extending prior modelling frameworks and addressing the need for models that can be applied to a broader spectrum of product transformations (as explored in RQ 1 & 2). In addition, we are one of the few studies using exergy losses as an environmental indicator to investigate the trade-off between profitability and environmental impacts of food valorisation. Adopting a supply- and demand-driven perspective extends the demand-driven focus of the existing literature and contributes to the discussion on optimising upstream waste management within the framework of the food waste hierarchy.

The model's applicability is demonstrated through a real-life case study from a carrot processing company in the Netherlands under consideration of several relevant scenarios and case settings, providing valuable insights for decision-makers in the agri-food industry seeking to improve their product portfolios. Our findings underscore the complex trade-offs in food valorisation. While side-stream valorisation enhances profitability, its environmental benefits are not necessarily guaranteed. Thus, food waste minimisation via valorisation to food products should not be seen as a goal but rather as a means to enhance sustainability and its potential depends on the type of product being valorised as well as the energy requirements of processing. Strategies such as optimising processing efficiency, refining harvest plans, and increasing demand flexibility can help mitigate these trade-offs.

From a practical perspective, these insights have meaningful implications for various stakeholders in the agri-food supply chain, including food manufacturers, retailers, food service providers and farmers. For food manufacturers, the adoption of a less demand-driven supply chain can improve resource utilisation, while simultaneously increasing profits. However, this requires contract adjustments with their customers and behavioural adaptations by consumers towards accepting products of varying quality. Manufacturers should also invest in energy-efficient processing, as the environmental benefits of valorisation depend largely on the energy requirements of the operations. Retailers and food service providers, on the other hand, can diversify their offerings with side-stream-based products, which may offer several benefits but requires flexible inventory management. Farmers can achieve more stable incomes by valorising a greater share of their produce. Despite these initial insights, continuous collaboration between industry, government, and researchers is crucial to scaling up valorisation efforts and advancing circular economy initiatives.

Despite its important contributions, this study has several limitations. Section 7 highlights, in this context, various areas of further research, which fall outside the scope of this study and require further investigation. For example, we suggest incorporating harvesting operations and farm-level environmental impacts into the scope of future research to better assess the potential of valorising harvest side streams. Additionally, developing systematic guidelines for selecting ingredients and processes that optimise both economic feasibility and environmental sustainability would provide valuable insights. Further research should also explore consumer acceptance of side-stream-based products, as attitudes towards side-stream-based products could affect market viability. In the context of viability, future studies should moreover evaluate the long-term financial viability of processing infrastructure investments through net present value analysis. Furthermore, to account for data uncertainty, future research should adopt stochastic or robust modelling approaches. Finally, expanding the model to include downstream supply chain dynamics, such as retail and food service distribution, would further enhance its applicability. By addressing these challenges, future research can further advance circular economy practices in the agri-food sector and beyond, ensuring a more sustainable and resource-efficient food system.

Table A.4
Data sources.

Data (parameter)	Core carrot products	Side-stream-based products
Supply (β)	Dutch vegetable processor	Literature (van Ravestijn, 1986)
Demand (δ^L&δ^U)	Dutch vegetable processor	Dutch vegetable processor (0 & 80% of average)
Returned value (ψ)	Dutch vegetable processor	Retailers (Table A.7)
Harvesting costs (c^H&c^U)	Dutch vegetable processor	Not applicable
Processing costs (c^P)	Dutch vegetable processor	Dutch vegetable processor (average)
Setup costs (c^S)	Not applicable	Literature (Duarte et al., 2021)
Purchasing costs (θ)	Dutch vegetable processor (Assumption 1)	Dutch vegetable processor (Assumption 1)
Processing exergy (e^O)	Dutch vegetable processor	Literature (Table A.8)
Product exergy (e^P)	Literature (Tables A.5 & A.6)	Literature (Tenorio et al., 2017)
Processing waste (ω^O)	Dutch vegetable processor	Dutch vegetable processor (average)
Recipes (γ & l & ϕ & π & λ & α)	Dutch vegetable processor	Retailers

CRediT authorship contribution statement

Marloes Remijnse: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Sonja U.K. Rohmer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Ahmadreza Marandi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Tom Van Woensel:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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Appendices

This paper includes 2 appendices. Appendix A provides the used data for the case settings and its sources. Appendix B provides additional Figures and Tables describing the results.

Appendix A. Data

See Tables A.4–A.8.

Table A.5
Specific chemical exergy of nutritional components.

Component	Specific chemical exergy (MJ/kg)	Reference
Water (l)	0.05	Szargut et al. (1988)
Protein	25.35	Apaiah et al. (2006)
Fat	43.09	Berghout et al. (2015)
Fibre	0.03	Zisopoulos et al. (2015)
Carbohydrates	16.70	Tenorio et al. (2017)

Table A.6
Nutritional composition of carrot (USDA, 2023).

Component	Content (kg/kg)
Water (l)	0.877
Protein	0.0094
Fat	0.0035
Fibre	0.031
Carbohydrates	0.103

Table A.7
Revenue per kilogramme of carrot in various side-stream-based products.

Article	Revenue (€/kg carrot)	Reference
Carrot top pesto	0.39	Albert Heijn (2023a)
Carrot top soup	0.35	Ecomondo (2023)
Carrot risotto	0.36	Albert Heijn (2023c)
Carrot chips	0.91	Albert Heijn (2023d)
Carrot wraps	0.45	Albert Heijn (2023h)
Carrot juice	1.30	Albert Heijn (2023i)
Carrot crackers	0.28	Albert Heijn (2023g)
Carrot puree	1.04	Albert Heijn (2023e)
Carrot puffs	0.11	Albert Heijn (2023b)
Carrot cake	0.09	Albert Heijn (2023f)
Carrot syrup	1.30	Jumbo (2023)
Carrot beer	0.79	WAAR (2023)

Appendix B. Results

See Tables B.9–B.11 and Figs. B.10 and B.11.

Data availability

The data that has been used is confidential.

Table A.8
Exergy input required for processing products at additional process lines.

Process line	Exergy input (MJ/kg output)	Based on product	Reference
Cake line	3.45	Fresh white bun	Zisopoulos et al. (2017)
Cracker line	4.02	Fermented brown bun	Zisopoulos et al. (2017)
Wrap line	3.24	Par-baked brown bun	Zisopoulos et al. (2017)
Juice line	1.03	Fresh sugar beet leaf juice	Tenorio et al. (2017)
Pesto line	1.43	Frozen juice	Tenorio et al. (2017)
Puree line	2.08	Ketchup	Ladha-Sabur et al. (2019)
Crisp line	17.3	Potato crisps	Ladha-Sabur et al. (2019)
Risotto line	7.30	Novel protein formulation	Apaiah et al. (2006)
Soup line	2.10	Pea soup	Apaiah et al. (2006)
Syrup line	2.10	Pea soup	Apaiah et al. (2006)
Beer line	2.10	Pea soup	Apaiah et al. (2006)

Table B.9
Pareto solutions HS and LS week, with the values of the efficient solutions shown in comparison to the max{Profit} solution (=100%).

LS week		HS week	
Profit %	Exergy %	Profit %	Exergy %
81	81	76	89
82	82	77	89
83	82	78	89
84	82	79	89
86	82	73	89
88	82	80	89
88	83	80	90
89	83	81	90
90	84	82	90
90	85	82	91
91	85	83	91
91	86	84	91
92	86	85	91
92	87	85	92
93	88	86	92
93	89	87	92
93	89	87	93
94	89	88	93
94	90	89	93
95	90	90	94
95	91	91	94
96	92	92	94
96	93	92	95
97	93	93	95
97	94	94	95
98	94	95	95
98	95	95	96
98	96	96	96
99	96	97	97
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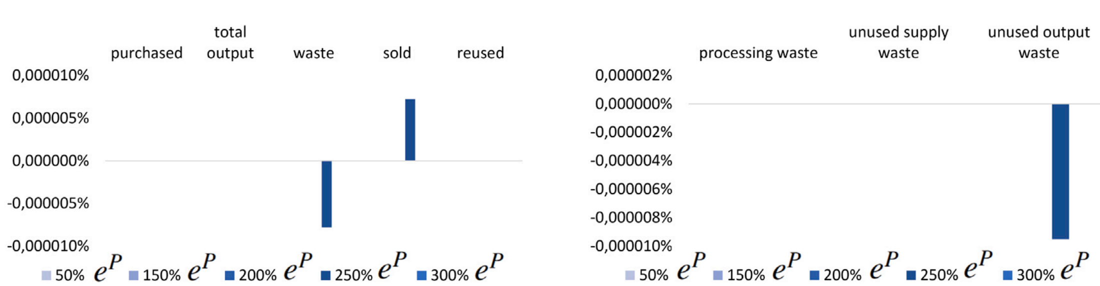
100	97	99	97
100	98	99	98
100	99	100	98
100	100	100	99
		100	100



(a) quantities (b) waste

Fig. B.10. Values corresponding to the solutions of the different product exergy losses e^P (in % to the Base Case values), optimising for the exergy loss (min{Exergy}) objective in the LS week.

Table B.10
Values corresponding to the solutions of different scenarios (in % to the base case values) in the LS week.

Scenario	Fluctuation	Objective	Total profit	Revenue	Process costs	Harvest costs	Purchase costs	Exergy Loss	Unused supply exergy loss	Unused output exergy loss	Process exergy loss	Process waste exergy loss	Purchased	Total output	Waste	Process waste	Unused supply waste	Unused output waste	Sold	Reused
c^H	50%	max{Profit}	91%	0%	−12%	−50%	−38%	−14%	0%	−8%	−25%	−3%	−4%	−18%	−7%	−3%	0%	−8%	0%	−49%
c^H	150%	max{Profit}	−83%	−1%	−2%	50%	48%	−3%	0%	−2%	−3%	−3%	−2%	−2%	−2%	−3%	0%	−2%	−2%	−3%
c^H	200%	max{Profit}	−165%	−2%	−2%	100%	96%	−3%	0%	−2%	−4%	−3%	−3%	−3%	−2%	−3%	0%	−2%	−2%	−3%
c^H	250%	max{Profit}	−247%	−2%	−2%	150%	145%	−3%	0%	−3%	−5%	−3%	−3%	−3%	−3%	−3%	0%	−3%	−3%	−4%
c^H	300%	max{Profit}	−329%	−2%	−3%	200%	193%	−4%	0%	−3%	−5%	−4%	−3%	−3%	−3%	−4%	0%	−3%	−3%	−4%
c^H	50%	min{Exergy}	125%	0%	0%	−50%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	150%	min{Exergy}	−125%	0%	0%	50%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	200%	min{Exergy}	−249%	0%	0%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	250%	min{Exergy}	−374%	0%	0%	150%	150%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	300%	min{Exergy}	−499%	0%	0%	200%	200%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,05	max{Profit}	7%	0%	0%	0%	−5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,2	max{Profit}	−14%	0%	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,3	max{Profit}	−27%	−1%	−1%	0%	18%	−1%	0%	−1%	−2%	−2%	−1%	−1%	−1%	−2%	0%	−1%	−1%	−2%
θ	1,4	max{Profit}	−40%	−1%	−2%	0%	26%	−2%	0%	−2%	−3%	−3%	−2%	−2%	−2%	−3%	0%	−2%	−2%	−3%
θ	1,5	max{Profit}	−54%	−1%	−2%	0%	35%	−3%	0%	−2%	−3%	−3%	−2%	−2%	−2%	−3%	0%	−2%	−2%	−3%
θ	1,05	min{Exergy}	10%	0%	0%	0%	−5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,2	min{Exergy}	−21%	0%	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,3	min{Exergy}	−41%	0%	0%	0%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,4	min{Exergy}	−62%	0%	0%	0%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,5	min{Exergy}	−83%	0%	0%	0%	36%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	50%	max{Profit}	100%	0%	−50%	0%	0%	1%	0%	1%	1%	1%	1%	1%	1%	1%	0%	1%	0%	1%
c^P	150%	max{Profit}	−96%	−1%	29%	0%	22%	−17%	0%	−10%	−28%	−6%	−6%	−19%	−9%	−6%	0%	−10%	−2%	−49%
c^P	200%	max{Profit}	−182%	−2%	72%	0%	20%	−17%	0%	−10%	−29%	−7%	−7%	−20%	−10%	−7%	0%	−10%	−3%	−49%
c^P	250%	max{Profit}	−266%	−2%	113%	0%	21%	−17%	150%	−11%	−29%	−8%	−7%	−21%	−10%	−8%	150%	−11%	−3%	−50%
c^P	300%	max{Profit}	−351%	−2%	155%	0%	21%	−17%	150%	−11%	−29%	−8%	−7%	−21%	−10%	−8%	150%	−11%	−3%	−50%
c^P	50%	min{Exergy}	105%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	150%	min{Exergy}	−105%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	200%	min{Exergy}	−210%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	250%	min{Exergy}	−315%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	300%	min{Exergy}	−420%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ω^O	25%	max{Profit}	39%	0%	−9%	0%	−15%	−19%	12%	−17%	−6%	−79%	−14%	−10%	−27%	−79%	12%	−17%	0%	−14%
ω^O	50%	max{Profit}	28%	0%	−6%	0%	−10%	−13%	8%	−12%	−4%	−55%	−10%	−7%	−19%	−55%	8%	−12%	0%	−10%
ω^O	75%	max{Profit}	15%	0%	−3%	0%	−5%	−7%	4%	−6%	−2%	−29%	−5%	−4%	−10%	−29%	4%	−6%	0%	−5%
ω^O	125%	max{Profit}	−17%	−1%	3%	0%	6%	6%	−5%	6%	0%	30%	5%	3%	10%	30%	−5%	6%	−1%	4%
ω^O	150%	max{Profit}	−36%	−1%	6%	0%	13%	14%	−10%	14%	2%	65%	11%	7%	23%	65%	−10%	14%	−1%	9%
ω^O	25%	min{Exergy}	49%	0%	−8%	0%	−14%	−20%	12%	−17%	−3%	−79%	−14%	−9%	−28%	−79%	12%	−17%	0%	−14%
ω^O	50%	min{Exergy}	35%	0%	−6%	0%	−10%	−14%	8%	−12%	−2%	−55%	−10%	−6%	−19%	−55%	8%	−12%	0%	−10%
ω^O	75%	min{Exergy}	18%	0%	−3%	0%	−5%	−7%	4%	−7%	−1%	−29%	−5%	−3%	−10%	−29%	4%	−7%	0%	−5%

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Table B.10 (*continued*).

Scenario	Fluctuation	Objective	Total profit	Revenue	Process costs	Harvest costs	Purchase costs	Exergy Loss	Unused supply exergy loss	Unused output exergy loss	Process exergy loss	Process waste exergy loss	Purchased	Total output	Waste	Process waste	Unused supply waste	Unused output waste	Sold	Reused
ω^O	125%	min{Exergy}	−21%	0%	4%	0%	6%	8%	−5%	7%	1%	32%	6%	4%	12%	32%	−5%	7%	0%	6%
ω^O	150%	min{Exergy}	−45%	0%	8%	0%	13%	18%	−10%	16%	3%	69%	13%	8%	25%	69%	−10%	16%	0%	13%
e^P	50%	max{Profit}	0%	0%	0%	0%	0%	−30%	−50%	−50%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	150%	max{Profit}	0%	0%	0%	0%	0%	30%	50%	50%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	200%	max{Profit}	0%	0%	0%	0%	0%	60%	100%	100%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	250%	max{Profit}	0%	0%	0%	0%	0%	91%	150%	150%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	300%	max{Profit}	0%	0%	0%	0%	0%	121%	200%	200%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	50%	min{Exergy}	0%	0%	0%	0%	0%	−33%	−50%	−50%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	150%	min{Exergy}	0%	0%	0%	0%	0%	33%	50%	50%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	200%	min{Exergy}	0%	0%	0%	0%	0%	66%	100%	100%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	250%	min{Exergy}	−8%	0%	0%	0%	4%	100%	150%	150%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	300%	min{Exergy}	0%	0%	0%	0%	0%	133%	200%	200%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	25%	max{Profit}	0%	0%	0%	0%	0%	−30%	0%	0%	−75%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	50%	max{Profit}	0%	0%	0%	0%	0%	−20%	0%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	200%	max{Profit}	0%	0%	0%	0%	0%	40%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	400%	max{Profit}	0%	0%	0%	0%	0%	119%	0%	0%	299%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	25%	min{Exergy}	0%	0%	0%	0%	0%	−25%	0%	0%	−75%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	50%	min{Exergy}	0%	0%	0%	0%	0%	−17%	0%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	200%	min{Exergy}	0%	0%	0%	0%	0%	34%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	400%	min{Exergy}	−9%	0%	0%	0%	4%	101%	2%	0%	300%	0%	0%	0%	0%	0%	2%	0%	0%	0%
δ^L	25%	max{Profit}	37%	−6%	−16%	0%	−23%	−20%	0%	−27%	−12%	−15%	−17%	−15%	−25%	−15%	0%	−27%	−7%	−12%
δ^L	50%	max{Profit}	31%	−4%	−13%	0%	−18%	−16%	0%	−24%	−8%	−10%	−14%	−12%	−21%	−10%	0%	−24%	−5%	−9%
δ^L	75%	max{Profit}	26%	−2%	−9%	0%	−12%	−13%	0%	−21%	−5%	−5%	−11%	−9%	−18%	−5%	0%	−21%	−2%	−4%
δ^L	25%	min{Exergy}	−67%	−71%	−73%	0%	−77%	−75%	0%	−77%	−72%	−74%	−77%	−73%	−76%	−74%	0%	−77%	−69%	−75%
δ^L	50%	min{Exergy}	−31%	−46%	−50%	0%	−53%	−53%	0%	−57%	−50%	−50%	−53%	−50%	−55%	−50%	0%	−57%	−44%	−50%
δ^L	75%	min{Exergy}	4%	−19%	−25%	0%	−27%	−30%	0%	−35%	−25%	−25%	−26%	−25%	−33%	−25%	0%	−35%	−17%	−25%
δ^U	125%	max{Profit}	53%	23%	16%	0%	15%	12%	−52%	4%	20%	20%	16%	16%	7%	20%	−52%	4%	23%	20%
δ^U	150%	max{Profit}	95%	46%	34%	0%	33%	29%	−81%	17%	41%	40%	35%	35%	21%	40%	−81%	17%	45%	41%
δ^U	175%	max{Profit}	132%	68%	54%	0%	53%	48%	−88%	34%	62%	60%	56%	56%	38%	60%	−88%	34%	68%	62%
δ^U	125%	min{Exergy}	33%	6%	0%	0%	0%	−6%	−52%	−10%	0%	0%	0%	0%	−9%	0%	−52%	−10%	8%	0%
δ^U	150%	min{Exergy}	43%	8%	0%	0%	0%	−8%	−81%	−14%	0%	0%	0%	0%	−12%	0%	−81%	−14%	11%	0%
δ^U	175%	min{Exergy}	44%	8%	0%	0%	0%	−8%	−88%	−14%	0%	0%	0%	0%	−12%	0%	−88%	−14%	11%	0%

Table B.11
Values corresponding to the solutions of different scenarios (in % to the base case values) in the HS week.

Scenario	Fluctuation	Objective	Profit	Revenue	Process costs	Harvest costs	Purchase costs	Exergy loss	Unused supply exergy loss	Unused output exergy loss	Process exergy loss	Process waste exergy loss	Purchased	Total output	Waste	Process waste	Unused supply waste	Unused output waste	Sold	Reused
c^H	50%	max{Profit}	336%	0%	−11%	−50%	−23%	−9%	0%	−8%	−21%	−2%	−6%	−16%	−4%	−2%	0%	−8%	0%	−41%
c^H	150%	max{Profit}	−320%	−2%	−2%	50%	43%	−2%	0%	−3%	−4%	−3%	−5%	−3%	−1%	−3%	0%	−3%	−2%	−4%
c^H	200%	max{Profit}	−637%	−2%	−3%	100%	87%	−3%	0%	−4%	−6%	−4%	−8%	−4%	−2%	−4%	0%	−4%	−3%	−5%
c^H	250%	max{Profit}	−954%	−2%	−3%	150%	133%	−3%	0%	−4%	−6%	−4%	−8%	−4%	−2%	−4%	0%	−4%	−4%	−6%
c^H	300%	max{Profit}	−1271%	−2%	−3%	200%	180%	−3%	0%	−4%	−6%	−4%	−8%	−4%	−2%	−4%	0%	−4%	−4%	−6%
c^H	50%	min{Exergy}	458%	0%	0%	−50%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	150%	min{Exergy}	−458%	0%	0%	50%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	200%	min{Exergy}	−916%	0%	0%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	250%	min{Exergy}	−1373%	0%	0%	150%	150%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^H	300%	min{Exergy}	−1831%	0%	0%	200%	200%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,05	max{Profit}	6%	0%	0%	0%	−4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,2	max{Profit}	−12%	0%	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,3	max{Profit}	−24%	−1%	−1%	0%	16%	−1%	0%	−1%	−2%	−2%	−3%	−2%	−1%	−2%	0%	−1%	−1%	−2%
θ	1,4	max{Profit}	−36%	−1%	−2%	0%	23%	−2%	0%	−2%	−3%	−2%	−4%	−2%	−1%	−2%	0%	−2%	−2%	−3%
θ	1,5	max{Profit}	−47%	−1%	−2%	0%	31%	−2%	0%	−2%	−4%	−2%	−4%	−3%	−1%	−2%	0%	−2%	−2%	−3%
θ	1,05	min{Exergy}	11%	0%	0%	0%	−5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,2	min{Exergy}	−22%	0%	0%	0%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,3	min{Exergy}	−44%	0%	0%	0%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,4	min{Exergy}	−66%	0%	0%	0%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
θ	1,5	min{Exergy}	−88%	0%	0%	0%	36%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	50%	max{Profit}	231%	0%	−50%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%
c^P	150%	max{Profit}	−222%	−2%	30%	0%	43%	−10%	2%	−11%	−25%	−8%	−12%	−19%	−5%	−8%	2%	−11%	−4%	−43%
c^P	200%	max{Profit}	−421%	−3%	72%	0%	41%	−11%	2%	−12%	−26%	−8%	−13%	−19%	−5%	−8%	2%	−12%	−4%	−43%
c^P	250%	max{Profit}	−618%	−4%	114%	0%	40%	−11%	3%	−13%	−27%	−8%	−14%	−20%	−5%	−8%	3%	−13%	−5%	−44%
c^P	300%	max{Profit}	−815%	−4%	156%	0%	40%	−11%	3%	−13%	−27%	−9%	−14%	−20%	−5%	−9%	3%	−13%	−5%	−44%
c^P	50%	min{Exergy}	264%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	150%	min{Exergy}	−264%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	200%	min{Exergy}	−529%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	250%	min{Exergy}	−793%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
c^P	300%	min{Exergy}	−1058%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ω^O	25%	max{Profit}	46%	0%	−8%	0%	−8%	−7%	13%	−11%	−6%	−79%	−13%	−9%	−8%	−79%	13%	−11%	0%	−17%
ω^O	50%	max{Profit}	36%	0%	−6%	0%	−7%	−5%	9%	−9%	−4%	−55%	−10%	−6%	−6%	−55%	9%	−9%	0%	−12%

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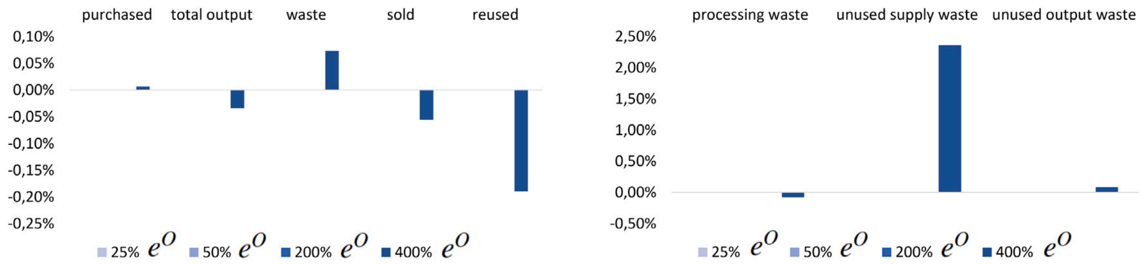
Table B.11 (*continued*).

Scenario	Fluctuation	Objective	Profit	Revenue	Process costs	Harvest costs	Purchase costs	Exergy loss	Unused supply exergy loss	Unused output exergy loss	Process exergy loss	Process waste exergy loss	Purchased	Total output	Waste	Process waste	Unused supply waste	Unused output waste	Sold	Reused
ω^O	75%	max{Profit}	20%	0%	−3%	0%	−4%	−3%	5%	−5%	−2%	−29%	−6%	−3%	−3%	−29%	5%	−5%	0%	−6%
ω^O	125%	max{Profit}	−22%	0%	3%	0%	4%	2%	−6%	5%	0%	30%	4%	3%	3%	30%	−6%	5%	−1%	5%
ω^O	150%	max{Profit}	−48%	−1%	6%	0%	8%	5%	−12%	11%	2%	65%	10%	6%	7%	65%	−12%	11%	−1%	11%
ω^O	25%	min{Exergy}	60%	−1%	−7%	0%	−15%	−6%	13%	−12%	−2%	−79%	−16%	−8%	−7%	−79%	13%	−12%	−2%	−14%
ω^O	50%	min{Exergy}	49%	0%	−5%	0%	−10%	−4%	9%	−10%	−1%	−55%	−11%	−5%	−5%	−55%	9%	−10%	0%	−10%
ω^O	75%	min{Exergy}	27%	0%	−3%	0%	−5%	−2%	5%	−5%	−1%	−29%	−6%	−3%	−3%	−29%	5%	−5%	0%	−5%
ω^O	125%	min{Exergy}	−32%	0%	3%	0%	6%	3%	−6%	6%	1%	32%	6%	3%	3%	32%	−6%	6%	0%	6%
ω^O	150%	min{Exergy}	−66%	0%	7%	0%	13%	6%	−12%	13%	2%	69%	14%	7%	7%	69%	−12%	13%	0%	13%
e^P	50%	max{Profit}	0%	0%	0%	0%	0%	−36%	−50%	−50%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	150%	max{Profit}	0%	0%	0%	0%	0%	36%	50%	50%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	200%	max{Profit}	0%	0%	0%	0%	0%	72%	100%	100%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	250%	max{Profit}	0%	0%	0%	0%	0%	108%	150%	150%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	300%	max{Profit}	0%	0%	0%	0%	0%	144%	200%	200%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	50%	min{Exergy}	−21%	−3%	−3%	0%	0%	−38%	−48%	−51%	−2%	−52%	0%	−3%	1%	−3%	5%	−2%	−2%	−5%
e^P	150%	min{Exergy}	0%	0%	0%	0%	0%	38%	50%	50%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	200%	min{Exergy}	0%	0%	0%	0%	0%	77%	100%	100%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	250%	min{Exergy}	0%	0%	0%	0%	0%	115%	150%	150%	0%	150%	0%	0%	0%	0%	0%	0%	0%	0%
e^P	300%	min{Exergy}	0%	0%	0%	0%	0%	153%	200%	200%	0%	200%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	25%	max{Profit}	0%	0%	0%	0%	0%	−21%	0%	0%	−75%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	50%	max{Profit}	0%	0%	0%	0%	0%	−14%	0%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	200%	max{Profit}	0%	0%	0%	0%	0%	28%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	400%	max{Profit}	0%	0%	0%	0%	0%	84%	0%	0%	300%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	25%	min{Exergy}	0%	0%	0%	0%	0%	−17%	0%	0%	−75%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	50%	min{Exergy}	0%	0%	0%	0%	0%	−12%	0%	0%	−50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
e^O	200%	min{Exergy}	−21%	−3%	−3%	0%	0%	23%	5%	−2%	96%	−3%	0%	−3%	1%	−3%	5%	−2%	−2%	−5%
e^O	400%	min{Exergy}	−21%	−3%	−3%	0%	0%	69%	5%	−2%	291%	−3%	0%	−3%	1%	−3%	5%	−2%	−2%	−5%
δ^L	25%	max{Profit}	13%	−1%	−3%	0%	−7%	−3%	0%	−7%	−3%	−2%	−7%	−3%	−3%	−2%	0%	−7%	−1%	−3%
δ^L	50%	max{Profit}	12%	−1%	−2%	0%	−6%	−3%	0%	−6%	−2%	−1%	−6%	−3%	−3%	−1%	0%	−6%	−1%	−2%
δ^L	75%	max{Profit}	12%	0%	−2%	0%	−5%	−2%	0%	−6%	−1%	−1%	−5%	−2%	−2%	−1%	0%	−6%	0%	−1%
δ^L	25%	min{Exergy}	−46%	−27%	−29%	0%	−91%	−27%	0%	−42%	−45%	−38%	−92%	−36%	−21%	−38%	0%	−42%	−44%	−12%
δ^L	50%	min{Exergy}	−31%	−20%	−22%	0%	−69%	−20%	0%	−31%	−33%	−26%	−69%	−27%	−15%	−26%	0%	−31%	−33%	−9%
δ^L	75%	min{Exergy}	−10%	−10%	−11%	0%	−34%	−10%	0%	−17%	−17%	−14%	−35%	−14%	−8%	−14%	0%	−17%	−15%	−6%
δ^U	125%	max{Profit}	153%	25%	24%	0%	25%	8%	−21%	19%	26%	25%	28%	25%	1%	25%	−21%	19%	24%	29%
δ^U	150%	max{Profit}	295%	49%	50%	0%	54%	18%	−42%	43%	53%	49%	60%	51%	4%	49%	−42%	43%	49%	59%
δ^U	175%	max{Profit}	425%	72%	72%	0%	88%	29%	−56%	65%	78%	71%	94%	74%	10%	71%	−56%	65%	72%	85%
δ^U	125%	min{Exergy}	164%	15%	13%	0%	0%	−3%	−21%	7%	8%	11%	0%	11%	−6%	11%	−21%	7%	10%	19%
δ^U	150%	min{Exergy}	316%	30%	28%	0%	0%	−5%	−43%	17%	17%	23%	0%	23%	−11%	23%	−43%	17%	18%	40%
δ^U	175%	min{Exergy}	451%	42%	36%	0%	0%	−6%	−56%	24%	22%	31%	0%	30%	−14%	31%	−56%	24%	23%	53%



(a) quantities

(b) waste

Fig. B.11. Values corresponding to the solutions of the different processing exergy losses e^O (in % to the Base Case values), optimising for the exergy loss (min{Exergy}) objective in the LS week.

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