Author(s): Wenger, Julia; Pichler, Stefan; Näyhä, Annukka; Stern, Tobias

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Practitioners' Perceptions of Co-Product Allocation Methods in Biorefinery Development—A Case Study of the Austrian Pulp and Paper Industry

Julia Wenger [1], Stefan Pichler [1], Annukka Näyhä [2,3] and Tobias Stern [1,*]

[1] Institute of Systems Sciences, Innovation and Sustainability Research, University of Graz, Merangasse 18/I, 8010 Graz, Austria; julia.wenger@uni-graz.at (J.W.); stefan.pichler@denkstatt.at (S.P.)
[2] School of Business and Economics, University of Jyväskylä, 40014 Jyväskylä, Finland; annukka.nayha@jyu.fi
[3] School of Resource Wisdom, University of Jyväskylä, 40014 Jyväskylä, Finland
* Correspondence: tobias.stern@uni-graz.at

Abstract: The utilization of coproducts is a strategy that can be applied to increase the economic and environmental performance of industrial processes and thus reach an objective targeted in several environmental policies. In multi-output production processes, allocation needs to be performed to assess the products' environmental and economic performance. It is crucial to choose an adequate allocation method, because this choice has been shown to strongly influence overall outcomes. Consequently, rash choices can lead to poor decision-making. Various ways to apply and combine allocation methods can be found in the academic literature, but it is often difficult to find sufficient guidance on how to choose an allocation method for a specific context. This study explores practitioners' perceptions of the cost and environmental impact allocation methods used in biorefinery development (lignin, fiber fines) by applying the analytic hierarchy process (AHP). Results indicate that professional background represents a major factor influencing individual preferences and, thus, the selection of specific allocation methods. Policy makers should be aware that practitioners with different professional backgrounds have varying preferences for different allocation methods and that this influences the overall assessments. These factors, in turn, affect the interpretation of results, further decision-making and, ultimately, the realization of environmentally sound and economically viable biorefinery projects. This issue deserves more attention in biorefineries, but also in other multi-output production processes. The findings indicate a need to consider multidisciplinary, diverse views and knowledge when conducting such assessments and to display the underlying approaches transparently.

Keywords: allocation of costs and environmental impacts; corporate environmental management; wood biorefineries; stakeholder perception; analytic hierarchy process (AHP); multicriteria decision-making

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1. Introduction

Biorefineries are viewed as being an important part of circular bioeconomy development, having the potential to contribute to the more sustainable use of environmental resources and, overall, to sustainability transition [1–3]. Several biorefinery definitions, approaches and developments exist [4], whereby the key aims are to be competitive in the market and replace fossil based products at the same time. In biorefineries, several products similar to the portfolios of crude oil refineries can be manufactured, but instead of fossil based oil, biorefineries utilize renewable resources [5]. The biorefinery concept includes various technologies that can separate such biomass resources (e.g., wood) into their building blocks (e.g., carbohydrates, lignin) [5]. These components can be further converted into various biofuels, chemicals, materials, feed and food, all of which have specific features, production costs, markets and prices [6,7]. Ahlgren et al. (2015) highlighted the need for various products to be coproduced in a symbiotic manner, allowing biorefineries to operate in a way that is economically, energetically and resource efficient. Nearly all types of biomasses can be utilized through various, jointly applied conversion technologies [5]. Lignocellulosic biomass (e.g., wood or residuals such as straw) accounts for most of the biorefinery concepts presented in scientific papers [4]. The consideration of feedstocks, such as industrial residues, lignocellulose and algae, has increased significantly in recent years. One of the key reasons is believed to be the food versus fuel debate and the broader search for more sustainable raw material sources [4].

Forest based biomass and the related new businesses are often central to a vision of the transition to the sustainable and circular bioeconomy, particularly in many forest rich countries [8,9]. Numerous studies have recently been carried out to analyze conceptual and methodological developments that are taking place during the transition to more sustainable biorefineries [5,7,10,11]. However, the results differ depending on, for example, site specific conditions, chosen technology, sustainability assessment methodology and the allocation basis in multifunctional processes [6,12–14].

In joint ("multi-output") production, allocation (i.e., the "*partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems*"; ISO 14044:2006 definition) is a necessity for companies, as it enables them to assess their products' performance (economic and environmental) [15]. It is crucial that they choose an adequate allocation method, because rash choices can lead to poor decision-making, such as when a more sustainable alternative to a product is sought, and the impacts of potential biorefinery products are considered and compared to those of the fossil based counterpart or other alternatives [16,17]. Various ways to apply and combine allocation methods can be found in the academic literature, and allocation is a heavily discussed topic in the literature on life-cycle assessments [14,18,19]. However, it is often difficult to find sufficient guidance on how to choose an allocation method in a specific context [20,21]. If more than one allocation method seems suitable for a production system, it may be useful to apply different approaches and to compare the outcomes [6,22]. However, the current and rather vague recommendations to apply the most "suitable" allocation method or to compare the outcomes of employing different options seem insufficient for practical application. Thus, a better understanding of the underlying decision-making process is needed. Accordingly, Frischknecht (2000) explained the important roles that subjectivity and value judgments played in the allocation procedure, because the allocation key can only be determined objectively in a few situations. The kinds of factors that actually influence the allocation method choice in practice (i.e., which methods are preferred) and the reasoning behind these choices are still unclear.

The sustainability impacts of biorefinery operations need to be assessed, and allocation(s) needs to be performed on a case to case basis, as the underlying conditions and assumptions are case specific and may influence the outcome [14,19]. Therefore, in the context of biorefineries and the sustainability of such operations, firms need to understand what allocation methods exist, how and why individuals choose particular allocation methods, and what kind of impacts these choices can have on the firms' calculated environmental performance and, accordingly, on strategic management decisions. More knowledge is needed about the issues affecting the choice of allocation methods in practice, for example, when developing more sustainable production processes, new business strategies, environmental management practices, or planning future operations in companies. In addition, increasing the knowledge and transparency regarding the choice of allocation methods in biorefineries helps relevant stakeholders, such as investors, policy makers, or customers, in their decision-making processes [13,23,24].

This study was carried out to determine the perceptions of practitioners (from Austrian pulp and paper companies) regarding how they would choose allocation methods in biorefinery development. The study outcomes, thus, bring practical perspectives into the prevailing academic discussion. Distinct characteristics of allocation methods that may guide the practitioners' choices were described in detail and structured. By using a multicriteria decision method called the analytic hierarchy process (AHP), the practitioners' preferences and context related perceptions were explored. More specifically, the following research questions were addressed in the study:

RQ 1: What are the distinct characteristics of allocation methods that may guide the practitioner's choice of allocation methods in biorefinery process development?

RQ 2: What preferences do practitioners in wood biorefinery process development have regarding the distinct characteristics of allocation methods?

RQ 3: How are these preferences based on context related perceptions induced by:

- product characteristics?
- type of impact (economic or environmental)?
- professional background?

Overall, this study was carried out to reveal another facet of the allocation issue, in particular, with regard to its application in the practical context of firms that deal with multifunctional processes. By connecting life cycle assessment (LCA) literature about allocation methods with empirical research on practitioners' viewpoints, we aim to contribute to more transparent and inclusive assessment approaches and, consequently, to cleaner processes and products from biorefineries and other multi-output production systems.

2. Materials and Methods

2.1. Wood Biorefineries with Multiple Product Outputs

On a larger scale, the separation of wood components takes place in wood pulping processes. These processes have, so far, mostly been developed and optimized for the extraction of cellulose [25]. The resulting lignin is available at an estimated quantity of about 40–50 million tons per annum globally (so called technical lignin), illustrating the global significance of this byproduct [26]. It is currently used mainly on site (about 95–98%) to obtain energy and recover the process chemicals [27], but is also expected to play major roles in biorefinery concepts in the future (e.g., in various kinds of material applications) [28]. Fiber fines are the smallest fraction of fibers (i.e., they can pass through a 200-mesh screen). These fines, which are generated during the pulping, bleaching and pulp-refining processes [29], account for only 3–8% of the kraft pulp [30] and were chosen as a complementary product to lignin in this study. The fines influence the properties of paper products; however, their separation is a topic of discussion (e.g., to save bleaching costs and for material applications) [29]. Currently, fiber fines are part of the pulp and are not (yet) separated from it. If this fiber fraction were separated, this would lead to a quantitatively small amount of obtained fines as compared to the biorefinery output of lignin (as lignin accounts for approximately 18–35% of wood) [31].

2.2. Allocation in Multifunctional Process Assessments

Frischknecht (2000) defined multifunctional processes as processes that contribute to multiple product systems. Coproducts are products of a joint production process that have a relatively high total sales value, while products that only have a low sales value as compared to others are referred to as byproducts [32]. A definition by Suh et al. (2010) suggests that the product should be considered as a byproduct if an increased demand for a product in joint production does not lead to an increase in the production volume due to its limited contribution to the total revenue [33]. However, the issue of allocating, for example, costs or environmental impacts of shared production to specific products prevails in such multiple product systems.

While the question of cost allocation in production processes was raised early on, the allocation of environmental impacts emerged within the context of the LCA during the first half of the 1990s (see [34]). LCA practitioners commonly need to address allocation issues, and particularly when multifunctional processes such as multi-output systems exist [19,35]. Choosing which allocation procedure to apply is one of the most extensively debated and controversial topics discussed among LCA practitioners, especially because it can have a significant impact on the outcome of an LCA study [19,36]. Even though the allocation methods are applied from both environmental and economic perspectives, their application has not often been discussed from both perspectives in the scientific literature. The economic and environmental burdens of joint production processes can be categorized by allocation method [13,19]. Two major procedures are mentioned in the scientific literature, namely, system expansion and partitioning methods [13].

System expansion refers to the extension of the initial production system boundaries to include a possible alternative production of the co- and byproducts in question (e.g., [19]). Regarding biorefinery co- and byproducts, the production of fossil alternatives can be used as reference products (e.g., biofuel versus conventional fuel). Figure 1 illustrates the idea behind system expansion, contrasting the defined main product of the production system and the coproducts with the avoided production of their reference product.

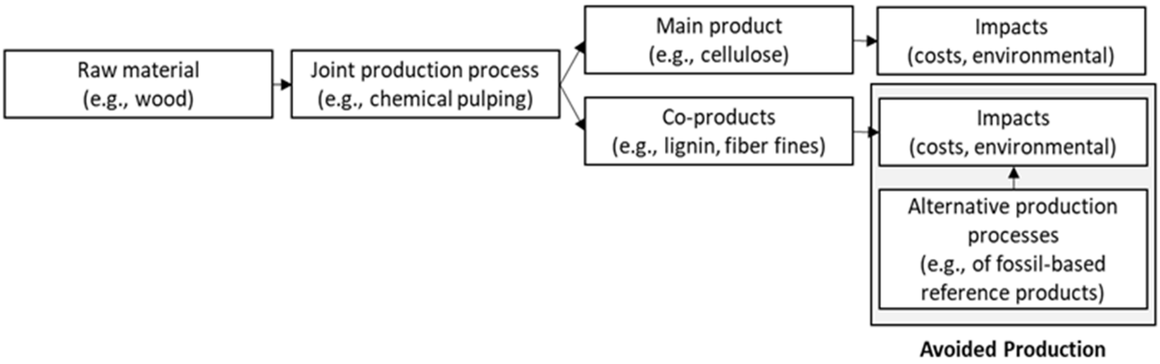

Figure 1. Schematic illustration of system expansion with respect to a joint production process, including one main product and various coproducts, as well as the potentially avoided production of substitutes for the coproducts (adapted from [19]).

When allocation is based on certain characteristics of the resulting co- and byproducts, this allocation is called partitioning [13]. Criteria frequently used for the partitioning method are the mass, volume, energy, exergy, or economic measures of the co- and byproducts (and combinations thereof) [19]. Figure 2 illustrates how partitioning can be applied to define the share of the impacts of each co-/byproduct in the production process, based on the energy content.

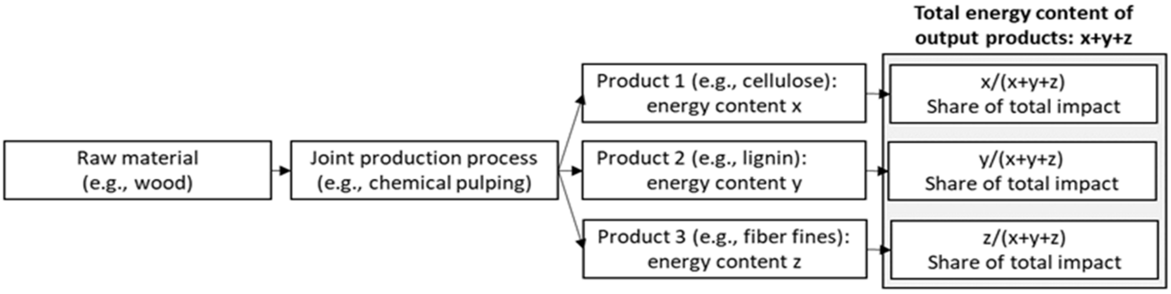

Figure 2. Schematic illustration showing how impacts are partitioned, based on the product energy content in a joint production process that includes three products (adapted from [19]).

Ekvall and Finnveden (2001) cited examples in which partitioning offers a better solution than system expansion and vice versa [37]. Heijungs and Guinee (2007) stated that system expansion is based on too many assumptions and, therefore, its usefulness as a scientific tool is debatable [38]. Weidema (2000), on the other hand, preferred system expansion over partitioning as an allocation method [17]. Guidelines for allocation procedures in multi-output processes exist [39,40], but in many contexts, such as those prevalent in biorefineries, several specific challenges, advantages, and disadvantages of respective allocation methods can be identified. These often lead to a lack of consensus in practice [14]. Allocation method choices can significantly influence the outcome of LCAs; this was demonstrated by Hermansson et al. (2020), who applied twelve different allocation methods to a study case on lignin (climate impact).

2.3. Strategic Decision-Making Process and Managerial Impact

Currently, the issue of managerial impact on decision-making is being studied in many disciplines. Recent research in the field of investment decision-making suggests that "human" aspects of decision-making [41], including the decision-makers' emotional acumen (e.g., [42]), are playing a significant role. The importance of the nature of human action has also been noted in studies on corporate environmental and sustainability related decision-making [24,43]. Schaltenbrand et al. (2018, pp. 129–130) stated "in an ideal world, managers would make decisions based on what is purely relevant to the situation at hand. They would initiate the decision making process by filtering out all irrelevant matter to prevent any form of partiality. Indeed, rooted in the view of homo economicus, the underlying assumption in corporate decision-making is that of managerial impartiality; decisions are made without the influence of any irrelevant matter. However, corporate decision making is more of an interpretive endeavor rather than an analytic computation." Overall, this statement also indicates that the managers' decision-making is affected by numerous issues. Despite the fact that the roles of individual managers and their interactions with the surrounding environments have increased in importance in many fields, the underlying determinants that affect managerial decisions in many contexts are still poorly understood [44].

2.4. Assessment of Allocation Preferences

To assess the allocation preferences of practitioners, a multicriteria decision-making approach was chosen. The AHP was developed by Thomas L. Saaty in the 1970s [45]. Saaty emphasized the importance of structuring decisions and accomplished this by arranging complex problems into a hierarchical structure: He placed an overall goal at the top, ranking the criteria and subcriteria below this, and placed the alternatives representing possible choices near the bottom [45,46]. The pairwise comparisons of (sub-)criteria and alternatives represent core elements of the AHP, whereby a rating scale from 1 to 9 was proposed by Saaty [45,46]; this scheme is illustrated in Table 1.

Table 1. Applied judgment scale (adapted from [45,46]).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Weak/Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong/Demonstrated importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Absolute/Extreme importance	The evidence favoring one activity over another provides the highest possible order of affirmation
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Applications of AHP are manifold and have been reviewed by Sipahi and Timor [47] and Ho and Ma [48]. The former noted that the use of AHP has increased significantly in various application areas, such as manufacturing, environmental management and agriculture [47]. Ishizaka and Labib [49] reviewed the methodological developments of AHP and discussed some of the method's advantages and disadvantages.

2.4.1. Development of the Hierarchy: Identification of Alternatives, Criteria and Sub-Criteria

AHP was performed to choose the most appropriate approach from a practitioner's individual viewpoint that could be taken to allocate the environmental impacts and costs of a biorefinery production process to two selected byproducts (goal). The most commonly applied allocation methods (alternatives) and their most prominent features were identified in a review of scientific papers on allocation issues. These features were summarized to form a smaller set of criteria and subcriteria for the sake of clarity and to reduce the risk of inconsistent answers. Thereafter, the hierarchy was derived, and this process is further described and illustrated in the Results section (Figure 3).

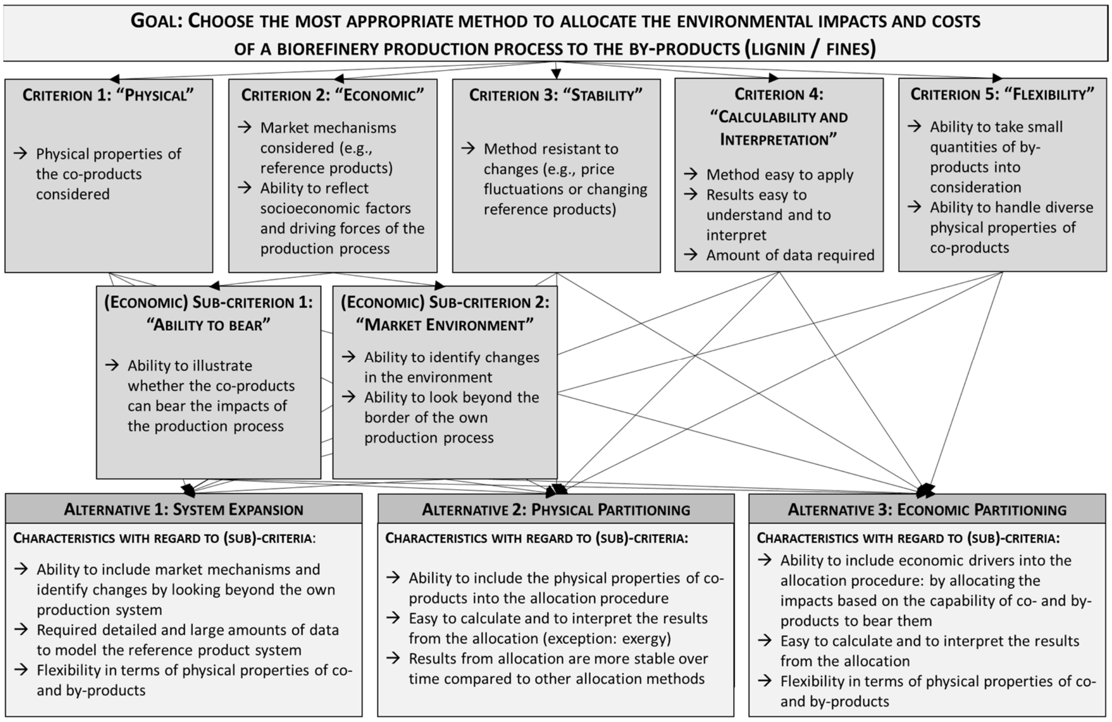

Figure 3. Structure and explanation of the AHP hierarchy, including the goal, criteria, subcriteria and alternatives.

2.4.2. Execution of the AHP

In this study, the rating scale shown in Table 1 was used, and the relative weights, consistency ratios (a measure for the consistency of the given pairwise ratings within a matrix) and final priorities were calculated as described by Saaty [50]. As a rule of thumb, Saaty (1987) stated that if the "consistency ratio exceeds 0.10 appreciably, the judgments often need reexamination" (Saaty 1987, p. 165). However, in practical fields such as managerial research, a consistency ratio (C.R.) lower than 0.2 can be considered as tolerable [51]; therefore, when a single judgment had a C.R. lower than 0.2, it was tolerated. Matrices with a higher consistency ratio were either excluded (criteria and subcriteria rankings by the interviewees) or the weighting was repeated (rankings of alternatives). The pairwise comparisons of the alternatives regarding the (sub-)criteria were drawn with reference to the scientific literature on allocation, as described in detail in the Results section. For the weighting of (sub-)criteria, experts were selected (s.f. Section 2.4.3). As the focus of this study was placed primarily on comparing the different practitioners' preferences regarding the (sub-)criteria rankings and the potentially different outcomes resulting from these, the respective individual judgments were used as the main basis for the analysis. In addition, aggregations of the judgments were also performed (with regard to the allocation type, byproduct and practitioners' professional backgrounds) using the geometric mean, as described and recommended by Saaty and Shang [52] and as performed by several authors regarding different topics [53]. This approach enabled us to attain quite low consistency ratios for the aggregated criteria rankings (the highest C.R. was 0.0308, described in detail in the Results section).

Microsoft Excel (Excel version 2108, Microsoft Office LTSC Professional Plus 2021, Microsoft Corporation, Redmond, WA, USA) was used to perform all AHP calculations, and R (R version 4.1.2, R Foundation for Statistical Computing, Vienna, Austria; RStudio version 2021.09.2, RStudio Inc., Boston, MA, USA; packages: base 4.1.2 and tidyverse 1.3.1) as well as Microsoft PowerPoint (PowerPoint version 2108, Microsoft Office LTSC Professional Plus 2021, Microsoft Corporation, Redmond, WA, USA) were used for the illustrations.

2.4.3. The Specific Cases of Lignin and Fiber Fines, and Involvement of Experts

The AHP was carried out on two different potential biorefinery (by-)products from the wood pulping process that are expected to have practical relevance: lignin and fiber fines. In addition to these two wood biorefinery byproducts, two subjects for allocations were investigated: the allocation of costs and the allocation of the environmental impacts to the byproducts.

Experts were identified and asked to perform pairwise comparisons of the criteria with respect to the goal (four pairwise comparisons per interviewed person: cost and environmental allocation for lignin and fines) and pairwise comparisons of the two subcriteria with respect to the economic criterium (also resulting in four pairwise comparisons per interviewee). Representatives were contacted from three different Austrian pulp and paper companies that were familiar with both lignin and fines due to their participation in related research project activities [54]. Within each company, people with three different professional backgrounds were taken into consideration (research and development, production, finance and controlling). Additional requirements for the selection of experts were: a profound knowledge level in their respective professional field (ideally, employees in management positions), familiarity with both lignin and fiber fines, and their availability and willingness to invest time to complete the whole survey consistently, which might be considered by some as burdensome [55]. Seven interviewees (three from R&D, two from production, two from finance and controlling) participated in the survey, which resulted in the collection of 26 responses, 21 of which were valid (the response composition appears in Table 2). The approach and survey were explained to the participants beforehand and conducted using the online survey web application tool LimeSurvey; if needed, additional calls were made by telephone to clarify the subject and procedure. The survey can be found in the Appendix: therewith, the criteria and corresponding subcriteria were compared pairwise to identify the respective preferences of the stakeholders. These ratings were then used to derive the matrices, and the AHP procedure was carried out [50].

Table 2. Composition of the sample (altogether, 21 valid matrices were derived from the answers of seven (7) participants who conducted pairwise comparisons of the criteria and subcriteria).

By-Product	Impact Category	Professional Background
Lignin (n = 10)	Costs (n = 10)	R&D (n = 7)
Fiber fines (n = 11)	Environmental impact (n = 11)	Production (n = 8)
		Finance and controlling (n = 6)

3. Results

3.1. Development of the Hierarchy: Identification of Alternatives, Criteria, and Sub-Criteria

The structure of the hierarchy, including the overall goal, criteria, subcriteria and alternatives, is explained and illustrated in Figure 3. The allocation approaches (alternatives) to be compared were system expansion, physical partitioning and economic partitioning. Nine potential features of allocation methods were identified in a review of scientific papers on allocation issues. These features referred to the consideration of market mechanisms (e.g., reference products, geographical context, changes in prices) [6,13,16,19,33]; considerations of the physical properties of coproducts [6,13,15,16,32]; method resistance towards changes, such as price fluctuations and changing reference products [6,13,19,22,56]; ease of applying the method [13,22]; ease of understanding and interpreting the allocation results (transparency) [13,57]; amount of data required [38,57]; ability to take small quantities of byproducts into consideration [22]; ability to handle diverse physical properties of the coproducts [6,16,58]; and ability to reflect on socioeconomic factors and/or driving forces for the production process [19,22].

Accordingly, the following criteria were defined to establish a hierarchy that could be applied to choose an appropriate allocation method: physical system [6,13,15,16,32], economic system [6,13,16,22,32,33,58], stability [6,13,19,22,56], calculability and interpretation [13,22,38,57] and flexibility [6,16,22,58]. The subcriteria ability to bear and market environment were then added to the economic criterion (hierarchy illustrated in Figure 3).

3.2. Pairwise Comparison of the Alternatives with Respect to (Sub-)Criteria

Referring to the selected scientific literature and the judgment scale given in Table 1, the three alternatives (economic partitioning, system expansion and physical partitioning) were compared pairwise with regard to the (sub-)criteria physical system, ability to bear, market environment, system stability, calculability and interpretation and flexibility. The resulting relative weights of the alternatives (allocation methods) with respect to the (sub-)criteria are illustrated in Figure 4 (consistency ratios: physical system, 0.0000; ability to bear, 0.0692; market environment, 0.1797; system stability, 0.0000; calculability and interpretation, 0.0000; flexibility, 0.0000).

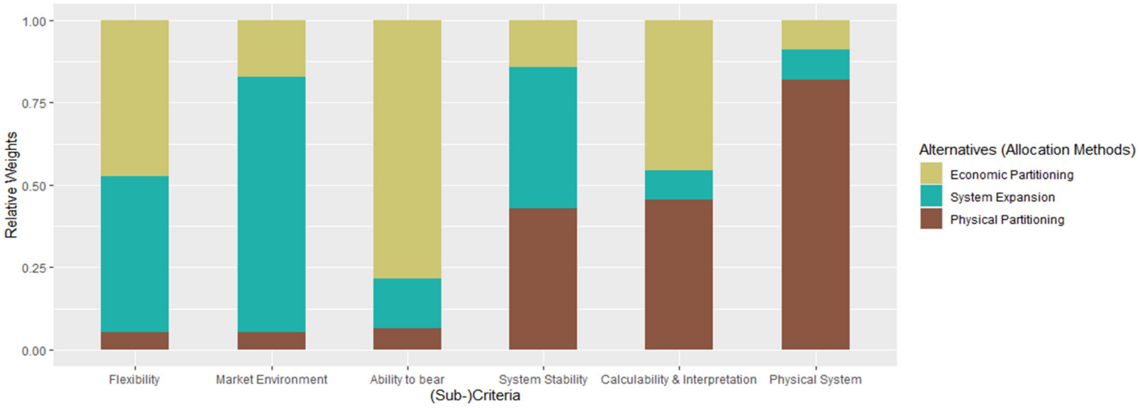

Figure 4. Relative weights of the alternatives (allocation methods) with respect to the (sub-)criteria.

3.3. Pairwise Comparison of the Criteria with Respect to the Goal

The execution of the pairwise comparisons by the biorefineries' representatives resulted in 26 responses, five of which were excluded due to inconsistencies (i.e., C.R. $\geq$ 0.2). The different criteria weightings assigned by the practitioners were compared to investigate their preferences, and the results were grouped to identify potential influencing factors (impact type, type of byproduct and the respective professional background). Regarding the overall results ($n = 21$), the respective relative weights of the five criteria are fairly balanced, with the criterion flexibility lagging slightly behind (using geometric means: system stability, 25.82%; economic, 21.07%; calculability and interpretation, 20.85%; physical system, 19.27%; flexibility, 12.98%; C.R.: 0.0046).

Only minor differences were observed in the weightings regarding the allocation type (cost allocation and environmental impact allocation) and the byproducts (lignin and fines); aggregated results (using geometric means) are given in Table 3 (Figure S1 on the respective weightings is provided in the supplementary material). Regarding the cost allocation (aggregated results), the criterion calculability and interpretation was assigned a lower relative weight, and the criteria economic and flexibility were given higher relative weights, as compared to the environmental impact allocation. The physical system criterion was rated as less important for fines than for lignin.

Table 3. Aggregated results (geometric means) of criteria weights with respect to the allocation subject (cost allocation: *n* = 10, environmental impact allocation: *n* = 11) and byproduct (fines: *n* = 11, lignin: *n* = 10).

	Calculability and Interpretation	**Economic**	**Flexibility**	**Physical System**	**System Stability**	**C.R.**
Cost A. (*n* = 10)	16.81%	23.18%	15.20%	18.49%	26.31%	0.0064
Env. I. A. (*n* = 11)	26.10%	18.48%	10.72%	19.94%	24.75%	0.0143
Lignin (*n* = 10)	19.76%	21.09%	12.36%	22.58%	24.20%	0.0042
Fines (*n* = 11)	21.79%	20.87%	13.45%	16.60%	27.30%	0.0088

On the contrary, major differences were noted regarding the different professional backgrounds of the participants (finance and controlling, production, research and development). This is illustrated in Figure 5, and the respective geometric means are given in Table 4. Most prominently, people with a background in finance or controlling ranked the economic criterion higher and the physical system lower than people from the production area and vice versa.

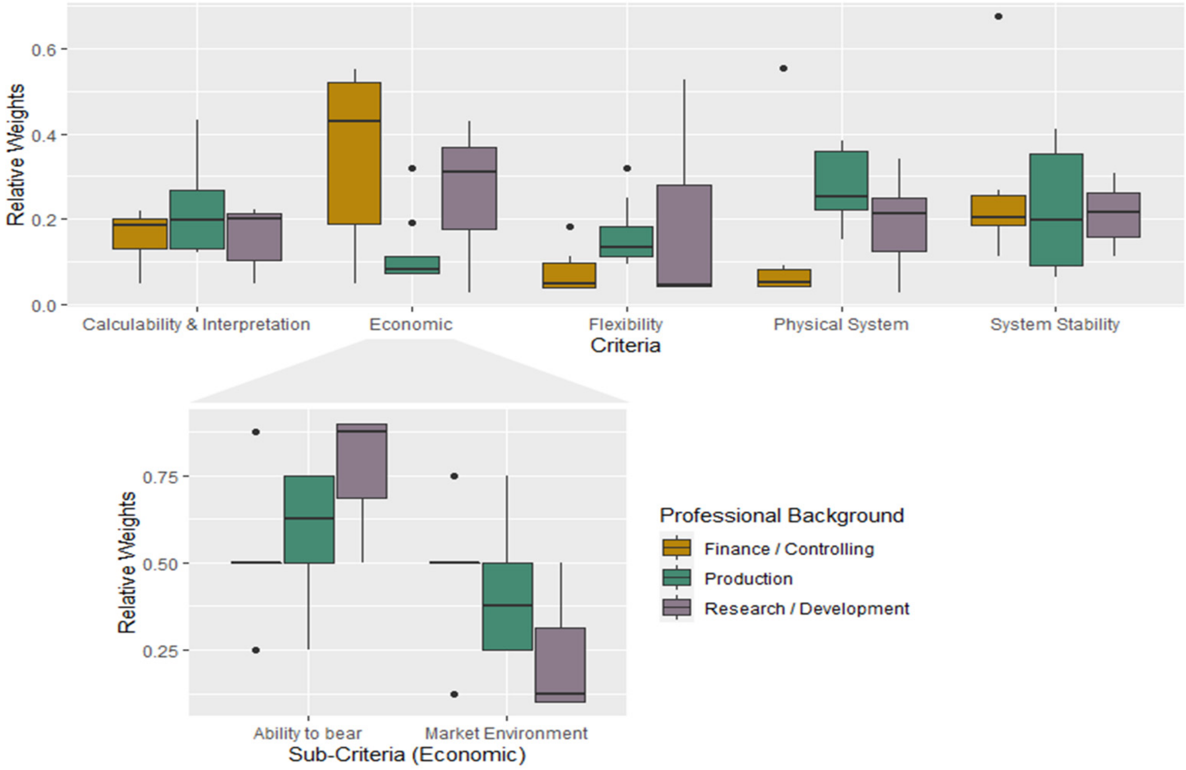

Figure 5. Weighting of criteria and subcriteria with respect to the professional background (finance/controlling: *n* = 6, production: *n* = 8, research/development: *n* = 7).

Table 4. Aggregated results (geometric means) of criteria and subcriteria weights with respect to the professional background (finance/controlling: *n* = 6, production: *n* = 8, research/development: *n* = 7).

	Calculability and Interpr.	Economic	Flexibility	Physical System	System Stability	C.R.	Ability to Bear	Market Env.
Finance and C. (*n* = 6)	18.66%	33.55%	8.29%	9.80%	29.69%	0.0308	53.52%	46.48%
Production (*n* = 8)	22.21%	11.92%	16.75%	28.80%	20.32%	0.0067	60.16%	39.84%
R&D (*n* = 7)	18.43%	24.09%	12.17%	19.10%	26.21%	0.0307	81.72%	18.28%

Concerning the weightings of the subcriteria with respect to the criterion economic (ability to bear and market environment), 21 consistent pairwise comparisons were obtained. The subcriterion ability to bear (ability of a method to use market prices, thus reflecting the ability of products to bear certain costs or environmental impacts, i.e., products with higher market prices also bear higher costs/environmental impacts) was rated higher than market environment (methods that are able to include changes in the market outside the production system) (overall *n* = 21), and using geometric means (ability to bear, 66.74%; market environment, 33.26%). As seen for the criteria, differences in the subcriteria weightings are also minor with regard to the different kinds of allocation (cost or environmental impact allocation; lignin or fines), but, again, are larger when comparing the different professional backgrounds. The latter aspect is illustrated in Figure 5, and the geometric means are given in Table 4. People with backgrounds in the fields of finance or controlling tended to rate both subcriteria as almost equally important, but production employees tended to weigh the importance of ability to bear more highly (60.16% vs. 39.84%), and research and development employees much more highly than market environment (81.72% vs. 18.28%).

3.4. Choice of Allocation Method

Regarding the final results for the 21 full AHPs, the final weightings of the respective alternatives are fairly balanced (illustrated in Figure S2), with a slightly higher weight assigned to the alternative physical partitioning (using geometric means: 38.31%), followed by economic partitioning (33.33%) and, finally, system expansion (28.37%).

As the results for the (sub-)criteria weightings show, only minor differences could be observed when comparing either the byproducts lignin and fines or the cost and environmental impact allocation (aggregated, all four would result in the choice of physical partitioning). However, differences become more evident regarding the professional backgrounds (illustrated in Figure 6).

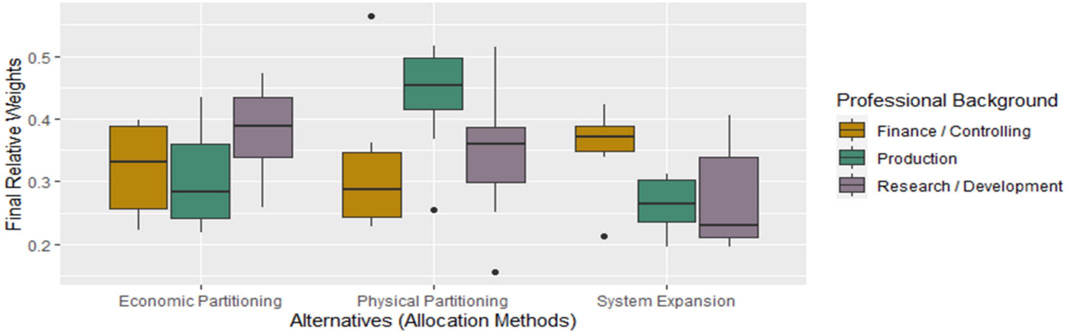

Figure 6. Final weights of the allocation alternatives with respect to different professional backgrounds of the interviewees (finance/controlling: *n* = 6, production: *n* = 8, research/development: *n* = 7).

Regarding allocation choices made on the basis of individual judgments (highest respective weights), people with a finance or controlling background preferred economic partitioning (3 out of 6 AHPs) over system expansion (2 out of 6) and physical partitioning (1 out of 6). People with a professional background in production, however, executed the (sub-)criteria weightings such that physical partitioning would have been chosen most of the times (6 out of 8 cases; 2 led to economic partitioning). Meanwhile, the judgments made by research and development employees resulted either in the choice of economic partitioning or physical partitioning (3 out of 7, respectively; 1 rating resulted in system expansion). The final choices derived from the aggregated results (using geometric means) led the aggregated professional groups production (43.98%) and R&D (37.41%) to choose physical partitioning for both, and led the aggregated group of practitioners from finance and controlling (34.35%) to choose economic partitioning.

4. Discussion

Unlike previous studies that applied different allocation approaches to compare the outcomes [6,14,22] or suggested new case specific approaches [59,60], this study applied user preferences regarding the identified (sub-) criteria to determine how allocation methods would be selected by practitioners.

The potential environmental or economic impacts of biorefinery implementations have been assessed several times [5,7,61]. However, major variations are observed in the results of these assessments, with allocation choices in multifunctional processes representing one of the key issues that affects the final outcome [6,13,14]. Both the companies themselves and their stakeholders assign importance to allocating costs and environmental impacts to the products. Thus, determining the respective impacts of and attaining information about each product in the production process is also important [19,23,62].

As a reasonable number of scientific papers are available that address the issue of allocation from various theoretical and applied viewpoints, it was possible to identify several distinct characteristics of allocation methods that may guide practitioners' choices (RQ1). Nine potential features were derived from these papers. Although some of these features are reported frequently (e.g., market mechanisms), others are cited as single cases (e.g., referring to small quantities of byproducts). Hence, this type of comprehensive overview was performed for the first time, allowing five criteria (and two subcriteria) to be defined that can be applied to choose allocation methods. The resulting decision hierarchy provides guidance on how an allocation method could be chosen easily and transparently for a specific context in practice.

The overall results of the assessment indicate that no clear preference for a specific allocation method could be identified among the participants (physical partitioning was favored slightly over economic partitioning and system expansion). Furthermore, the different criteria (based on methodological characteristics), which were relevant for the selection of allocation methods (as shown in Figure 3), were rated rather indifferently, with most average weights (geometric means) hovering around 0.2 (RQ2). Only the criterion flexibility was perceived as relatively less important, and system stability as slightly more important.

The respondents weighted the criteria for allocation method selection in different ways: the economic criterion showed higher levels of variation than calculability and interpretation, which indicates that the less constant factors might be more decisive under variable conditions. To a certain degree, these results may reflect (or are reflected by) the ongoing academic discussion on allocation methods [14,19,63]. High ratings assigned to the criterion market environment (subcriterion of economic) and—to some extent—flexibility, favor system expansion, while ability to bear (subcriterion of economic) favors economic partitioning (Figure 4). This finding reflects those of Ekvall and Finnveden [37], who showed the better fit of certain allocation procedures in specific situations. According to Heijungs and Guinee [38], the strength of system expansion in terms of flexibility and consideration of the (dynamic) market environment [17] is also its disadvantage, depending on the suitability for specific tasks. Hence, the results in this study also confirm the context dependency of the selection of allocation methods.

How exactly did context factors influence the allocation method preferences of the responding practitioners? The study results are quite mixed. Neither the product characteristics nor the type of considered impact (environmental or cost) seem to provide consistent evidence for an influence on practitioners' preferences. The results in this respect are surprisingly homogeneous (see Table 3 and Figure S1). Considering the rather distinct discussion and development of cost and environmental impact allocation (see [34]), this result is somewhat unexpected. It could also have been expected that the product characteristics (e.g., large vs. small volume products) would influence the preferences for the criteria physical system or economic. Indeed, the average preference for physical system was higher for lignin (large volume) than for fines (small volume), but the difference was rather small. The criterion calculability and interpretation was also rated as slightly higher with regard to environmental impact allocation as compared to cost allocation (possibly due to the comparably broader interpretability of the term "environmental impact"). All in all, this study did not reveal empirical evidence that practitioners' preferences for certain allocation methods are substantially governed by variations in considered products or impacts.

Although influencing factors regarding product or impacts were not distinctly identified, the clear influence of the respondents' professional backgrounds can be considered a key finding of this study. In other words, the professional background can be considered as a major factor in contextualizing allocation preferences. Respondents working in the field of production favored the physical system and, hence, preferred taking physical partitioning approaches, while their counterparts from finance and controlling favored the economic criterion (considering both its subcriteria nearly equally), making economic partitioning and system expansion the more preferred approaches. Respondents working in research and development (R&D), meanwhile, assigned ratings in a rather balanced way (but focused much more strongly on the subcriterion ability to bear): their judgments mostly fall between those of the other two professional groups, with the most preferred allocation methods identified as physical partitioning and economic partitioning. Subjectivity in allocation choices, as detected in this study, strengthens the view of LCA as an interpretative process [64] in which the reasoning, views and choices behind these need to be understood more fully than is currently often the case.

These findings from our study are supported by the strategic management field and its core theoretical premises of decision-making: the role of individual managers is essential in strategic decision-making in firms, and managerial decisions are affected by numerous, human related factors, such as the managers' skills and capacities or maybe even their daily routines. These results also reflect other results published in the corporate decision-making literature, including in the paper by Schaltenbrand et al. [43], who stated that corporate decision-making is more of an interpretive endeavor than an analytic computation. In the other words, we need a fuller understanding of selective perceptions [65] and various determinants in managerial decision-making [44,66]—all of which have an impact on the choice of allocation methods—for strategic management in biorefinery companies. To our knowledge, these issues have neither been addressed by researchers conducting biorefinery LCAs nor by those looking at allocation choices made in the other fields. Although these findings revealed the relevant effect of the professional background on preferences for allocation methods, the underlying drivers and more specific attributes for this observation have not yet been identified. This would require more research approaches to be taken in the future, including qualitative social research approaches such as the laddering technique [67].

Despite making several requests, we did not manage to involve more participants in the study. This could have been due to their time constraints and unfamiliarity with the topic of impact allocation and/or the type of questioning (i.e., the pairwise comparisons). In addition, the tasks of answering the questions and assigning consistent ratings might have been perceived as burdensome. Therefore, the results cannot be considered as representative; however, this was also not intended considering the quasi-experimental nature of the study. As the participants from the companies were not familiar with the impact allocation literature and with the process of comparing allocation alternatives with respect to certain criteria, the pairwise comparisons of the alternatives regarding the (sub-)criteria were performed with reference to the scientific literature on allocation issues. This was found to be an appropriate information base for this task, and also made the process more objective and transparent.

5. Conclusions

This study provides valuable information about this relevant but rarely studied issue by exploring the practitioners' perceptions of allocation methods in biorefinery development. Specifically, we gathered information on the perceptions of Austrian pulp and paper company representatives regarding their choices of appropriate allocation methods.

The practical implication of the study findings is that different allocation procedures can be preferred or applied within one company, one biorefinery, one product and even one impact category. Furthermore, the relevance of professional background to allocation related decision-making suggests that environmental managers and other decision-makers (e.g., in firms) should be properly trained on allocation issues and their implications. The versatile combination of capacities, skills and other human factors would enable allocation options to be viewed from multiple perspectives. In this way, more conscious decisions, which are not bound to single manager's or department's perceptions, could be formulated. Subramanian et al. [68], for example, emphasized that implementing meaningful decision models that can have positive environmental and economic impact should involve all departments in a business, as well as industrial ecologists and business managers.

Policy makers—for example participating in decision-making processes on European Union research projects and demonstration plants—should be aware that practitioners with different professional backgrounds can have various perspectives on and preferences for allocation methods, and that this may influence the results of environmental and cost assessments significantly. This, in turn, affects the interpretations and decisions made by these practitioners and by the policy makers themselves. It is therefore recommended that, in biorefinery research and implementation, multidisciplinary and diverse views and knowledge are included in the assessment of both the environmental impacts and the costs—and, thus, also the reasonableness and feasibility—of such projects. Through interdisciplinary work and communication, urgently needed common allocation principles for practitioners could be developed, thus allowing them to respond better to the current challenges.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14052619/s1; Figure S1: Weighting of criteria with respect to the allocation subject (cost allocation: n = 10, environmental impact allocation: n = 11) and byproduct (fines: n = 11, lignin: n = 10); Figure S2: Overall results (n = 21) of the AHPs (final weights of the alternatives); survey on the topic of cost and environmental allocation in biorefinery processes.

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