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Barriers to Sustainable Manufacturing in the Chemical Industry: A Qualitative Study

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Abstract: The manufacturing industry accounts for at least 20% of global CO_2 emissions, making it a key player against global warming. But despite significant progress, the industry still faces barriers preventing the adoption of more sustainable processes. To identify these barriers, we interviewed 15 decision-makers in the specialty chemical and pharmaceutical industry, isolating the criteria driving their decisions and how these interact with sustainability. We found three main barriers to sustainable manufacturing: the lack of a standardised way to measure sustainability; the lack of a holistic approach to sustainability encompassing economic, environmental, and social factors; the lack of economic incentives to adopt more sustainable practices. While a tax on externalities (such as emissions) would ensure the consideration of sustainability in decision-making, it requires solving all three barriers to be implemented effectively. In the meantime, we propose the use of decision support systems such as multicriteria decision analysis (MCDA) as an easy way to account for sustainability while facilitating a trade-off between it and costs.

Keywords: sustainable manufacturing; barriers to sustainability; criteria; manufacturing; chemical manufacturing; MCDA

1. Introduction

A decade ago, world leaders agreed to limit global warming to 2.0 degrees Celsius [1]. This would require not only limiting but also significantly reducing greenhouse gas emissions, an objective we have so far failed to achieve [2,3]. Currently, efforts to reduce emissions are concentrated on the most carbon-intensive human activities, as any reduction in these areas can potentially have a large global impact. The manufacturing sector is one of these areas. As of 2014, the manufacturing and construction sector accounted for 20% of global emissions of greenhouse gases [4].

The idea of making manufacturing sustainable is not new, but it still has not been realised. In 1987, the UN defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" [5]. Since then, a growing body of the scientific literature has explored the concept of sustainability [6], proposed ways to measure it [7], and recommended approaches to make manufacturing more sustainable [8], among many other research streams. But despite almost four decades of research, and significant technical development [9–11], there still is much untapped potential [12,13], and we still face greenhouse gas emission levels inconsistent with international goals [3].

Why, despite significant effort, has sustainable manufacturing not yet been achieved? What are the barriers preventing the manufacturing industry from being more sustainable?

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What tools or methodologies could help overcome these barriers? We attempt to answer these questions using the chemical industry as a case study. Chemical manufacturing is responsible for about 5% of global greenhouse gas emissions and is considered difficult to decarbonise due to its reliance on carbon-rich raw materials and its need for high temperatures in its processes [14]. These challenges make chemical manufacturing an intensively studied area for decarbonisation and sustainability [9,15–19] (among many others) and a good study subject to identify barriers to sustainable manufacturing and how to overcome them.

The objective of this study is to identify the main barriers to sustainability in the chemical manufacturing industry. To achieve this, we study the decision-making process used in it and what role sustainability considerations play in it. The hypothesis is that, even though there may be sustainable technological solutions available (e.g., a greener chemical process), decisions are made to use less sustainable ones. The factors or criteria driving such decisions constitute barriers for sustainable manufacturing. Therefore, in this study, we begin by identifying the main criteria used by decision-makers in the chemical manufacturing industry, and then we explore how they relate with, and potentially antagonise, sustainability. We also identify potential tools or methodologies that can help overcome these barriers, from the perspectives of practitioners themselves. We do this through a qualitative study because we are interested in practitioners' perspective on the problem, and as [20] state, qualitative methods are appropriate when there is a "need to understand the settings or contexts in which respondents (. . .) can address/outline an issue or problem". We use semi-structured and narrative interviews [21] to give decision-makers freedom to narrate their decision-making process using their own words and from their own perspectives.

The rest of the document is organised as follows. Section 2 presents a brief literature review on the identification of barriers and potential enablers to sustainability in the manufacturing industry. Section 3 describes the methodology used to collect and analyse the semi-structured interviews that form the basis of this work. Section 4 presents the results of the analysis. Section 5 discusses the results from this study in comparison to the published literature, and Section 6 presents a brief summary of this study, its conclusions, and the practical recommendations for decision-making in the manufacturing industry.

2. Literature Review

In this section, we review the main research trends on sustainable manufacturing during the last two decades, focusing on the major barriers to implementation found by multiple studies.

2.1. Identifying Barriers to Sustainable Manufacturing

In the late nineties, over a decade after the UN defined sustainable development, [22] surveyed the literature, identifying key issues in "environmentally conscious" manufacturing. They identified three main barriers to the implementation of sustainable practices. First, the lack of decision tools that adequately capture the unique objectives and indicators of sustainability. Secondly, the lack of profitability in sustainable systems. Third, the lack of a holistic research approach to sustainability, incorporating not only physical sciences but also engineering and operations research. These three barriers—a lack of standardised tools to measure and address sustainability, a lack of economic incentives, and a lack of a holistic approach—were refined in later research.

In an attempt to develop a holistic framework for sustainability, refs. [23,24] promoted the concept of life cycle assessment (LCA). This approach attempts to quantify the total environmental impact of manufacturing a good or providing a service, by taking into account all the negative environmental externalities throughout its life cycle. This begins with the extraction of natural resources, their pre-processing and transportation, manufacturing emissions and waste, distribution emissions, pollution due to its use, and finally, due to it being discarded, among any others along the life cycle of the product. While very robust and holistic, this approach is not easy to implement, requiring large amounts of information for which there were no international databases and no tools to facilitate and standardise its implementation.

2.2. The Need for Standardisation

By the early 2010s, the literature on sustainable development had expanded and specialised into multiple areas, yet it still lacked a standard way of measurement. Ref. [25] identified multiple sub-areas of sustainability (e.g., product design, supply chain, waste avoidance, etc.), which shared two main difficulties: a lack of connection between academic (theoretical) and actual industrial work and a lack of standardised measurements. They found that while the industry did report metrics of environmental performance, these lacked standardisation and were often chosen based on the nature of the task, making comparisons across projects difficult. The need for standard measures of sustainability was also highlighted by [26] in the context of life cycle assessment, and by [27–29] in the context of decision support systems used to facilitate decision-making in manufacturing, as these tools benefit from the use of quantifiable criteria that are familiar to users (i.e., standardised measures). Ref. [30] surveyed researchers and industry professionals, also identifying the lack of standardisation as a major barrier to sustainable manufacturing, along with a lack of knowledge about sustainability concepts, a high cost of implementation, and an unclear demand for sustainability by the final consumer.

The lack of standardisation has practical negative consequences. Ref. [8] concluded that the lack of standardisation of energy-efficiency measures and the lack of economic incentives caused users, operators, and designers of industrial machinery to not pay enough attention to efficient energy usage. Indeed, they estimated that manufacturing energy consumption could be reduced by up to 50% using existing technology.

2.3. The Need for a Holistic View and Tools

Most of the literature seen so far concentrates on the environmental dimension of manufacturing sustainability, but a wider understanding of it encompasses three dimensions or pillars: social, economic, and environmental [6]. The social pillar refers to the impact of manufacturing on both labourers and the larger community. The economic pillar involves the aspects most commonly associated with manufacturing, such as costs, investments, and profitability. Finally, the environmental pillar involves the environmental consequences or externalities of manufacturing, including emissions, waste, etc.

In practice, however, sustainability's multidimensionality is often ignored, so multiple authors have proposed using decision support tools to facilitate the simultaneous consideration of multiple pillars. Ref. [31] highlights how most sustainability assessments focus solely on the environmental pillar, so instead, they propose using a decision support tool integrating environmental, economic, and social aspects, each with a weight or relevance defined by the users (i.e., the decision-maker) themselves. Refs. [29,32] both perform a literature review on decision tools used to support sustainable manufacturing decisions, finding the social pillar to be often neglected at the operational level, while the economic pillar tends to dominate decision-making.

Multicriteria decision analysis (MCDA), a particular family of decision support tools, is proposed as an effective way to implement a holistic approach to sustainability by [33–36]. MCDA allows the simultaneous consideration of multiple sustainability metrics, each weighted according to the decision-maker's preferences, which can vary across stakeholders, industries, and geographic areas [37]. This approach is applied to waste management by [38].

The concept of the circular economy (CE) is another attempt at a holistic understanding of sustainability. The CE aims for a "closed loop of material flow in the whole economic system" [39], meaning that resources are re-used at a large scale, minimising the environmental impact of manufacturing. But as ref. [40] discuss, the CE can also tackle the scarcity of resources because they are re-used instead of being spent, which can benefit the profitability of industry by reducing provision, supply chain, and waste management costs. Hence, the CE can fulfil both the economic and environmental pillars of sustainability and may even comply with the social pillar if its implementation benefits local communities by, for example, implementing local recycling plants that boost labour demand. Ref. [39] identify several barriers to the implementation of the CE. First, changes in tax policy may be required to make recycling more economically attractive than the extraction of virgin resources. Second, further technological development is needed to make recycling more efficient. And finally, customer and final users must be educated and incentivised to recycle.

Advanced manufacturing is another holistic approach to sustainable manufacturing, aiming to optimise production through the coordination of information, automation, and computation, starting from product development and throughout the whole product's life cycle. It was proposed by [10], who identified two main barriers against it: the lack of data on emissions and energy consumption, and the lack of a supply chain-wide approach, capable of optimising production across the products' whole life cycle. Refs. [41,42] echo the importance of an integrative and holistic optimisation approach to manufacturing, but under the moniker of Industry 4.0 (i.e., the use of smart automation in industry), highlighting its responsiveness and efficiency.

2.4. The Lack of Economic Incentives

The potentially high cost of sustainable manufacturing is often identified as a barrier to its implementation. Ref. [11] underscore how lean (i.e., optimised) manufacturing is one of the main drivers of sustainability among small- and medium-sized firms. However, firms of these sizes require funding support (e.g., tax loans) to implement the necessary technology to achieve it. Even large companies may have problems financing new technologies such as carbon capture and hydrogen production, as discussed by [13], who propose setting up dense industrial clusters to share the cost of some of these more expensive technologies.

2.5. Summary and Gaps

The literature identifies three main barriers to sustainable manufacturing: (i) the lack of standardised measurements of sustainability; (ii) the lack of a holistic, system-wide, approach to sustainability, encompassing product design and the whole life cycle of the product from an economic, environmental, and social perspective; (iii) the lack of economic incentives to implement often costly sustainable manufacturing technologies. The first two barriers are closely linked, as they reflect the lack of a standardised methodology for assessing sustainability. Such methodology should be flexible enough to adapt to many different scenarios while simple enough to be accessible.

Despite presenting multiple different potential methodologies to assess sustainability (e.g., life cycle assessment, MCDA, circular economy, Industry 4.0), the literature does not offer enough clues on what requirements such a methodology should satisfy from the perspective of its potential users (practitioners). By understanding practitioners' decision-making processes, this work attempts to identify key requirements for a methodology to assess and encourage sustainable manufacturing.

3. Materials and Methods

Participants of this study were professionals working in the chemical industry who routinely made decisions on setting up or modifying production lines, choosing chemical routes for production, and deciding on outsourcing, infrastructure investments, etc. They were recruited by either (i) a large European specialty chemical company that invited its own employees to participate, or (ii) a British knowledge-transfer consortium of chemical companies that invited clients and associates to participate. No incentives were offered to participants.

Recruitment rendered 15 participants, with a mean of 18 years of experience in the chemical industry. Table 1 summarises the industry, location, experience, and area of work of each interviewee in their respective companies. All participants were experienced contributors to the decision-making process, with significant levels of responsibility within their companies. While 15 is a small sample size, it was enough to reach saturation, the most common approach to determine a sufficient sample size in qualitative research [20,43,44].

Table 1. List of interviewees.

Industry	Location	Subject	Experience	Area of Work
Specialty chemical	Europe	S11	6 years	Process technology
Specialty chemical	Europe	S14	11 years	Environmental manager
Specialty chemical	Europe	S1	13 years	Process development
Specialty chemical	Europe	S8	13 years	Process development
Specialty chemical	Europe	S7	20 years	Sourcing (supply chain)
Specialty chemical	Europe	S12	30+ years	Process development
Specialty chemical	UK	S9	11 years	Process development
Specialty chemical	UK	S3	33 years	Process hazard
Specialty chemical	USA	S2	10 years	Process technology
Specialty chemical	UK	S10	39 years	Operations manager
Pharmaceutical	UK	S5	15 years	Validation engineer
Pharmaceutical	UK	S15	15 years	Process technology
Pharmaceutical	UK	S4	16 years	Process technology
Pharmaceutical	UK	S13	16 years	Process development
Pharmaceutical	UK	S6	27 years	Process development

All participants were interviewed remotely through video call at a time suitable to them and agreed in advance. They were asked to be prepared to discuss the following topics during the interview: (i) introducing themselves, (ii) describing their latest experience making a manufacturing decision, (iii) discussing how they arrived at a decision and what criteria determined that decision, and (iv) to think about tools that could help them make faster and better decisions in the future.

These interviews were part of a larger effort to understand decision-making in the chemical manufacturing industry; hence, prospective participants were not briefed on sustainability being one of the aspects to discuss. This prevented biassing the sample towards individuals with favourable attitudes towards sustainability.

The interviews were semi-structured. After a brief introduction detailing the context of the study, participants were asked to complete a consent form before starting the discussion, which centred around the following questions.

1. Could you introduce yourself, including your role at the company?
2. What is the latest manufacturing decision you made, or a recent one you consider interesting?
3. Could you have made a different decision? What were the other potential alternatives?
4. Why did you choose that alternative, and not others?

5. Did you consider any of the following criteria when making your decision: fixed cost, variable cost, throughput, safety, quality, uncertainty, set-up time, batch size, environmental impact, supply chain reliability? (These criteria were extracted from the literature, and they were only asked for if not mentioned unprompted by the interviewee).
6. What was the most difficult thing when making the decision?
7. How did you face that difficulty? Could it be made easier?
8. Have you ever used decision support tools? If so, which?
9. Is there anything else you would like to discuss related to the decision-making process?

While the interviews were semi-structured, they also included a strong narrative component [21]. In particular, participants were asked to narrate the latest (or one of the latest) manufacturing decisions they had to make very early in the interview. This allowed the discussion to be anchored in an actual decision instead of generalisations. At the same time, the narration of the decision naturally highlighted the most relevant aspects of the decision process from the interviewee's perspective. As the narrative constituted the backbone of the interview, the questions above were mostly used as prompts and as a checklist to ensure that all relevant aspects were discussed in all interviews, but a fluent discussion centred on the narrative was always favoured over a strict following of the script. The script, interview, and recording storage protocol were evaluated and approved by the corresponding ethics committee at the University of Leeds.

Interviews were recorded and transcribed in all but one case. The only exception (S15) was due to the interviewee not giving consent for the recording. Nevertheless, notes were taken during that interview, and later, analysis revealed great consistency between this interview and the rest.

The analysis of interviews followed the thematic coding scheme proposed by [21]. The analysis begins by summarising the basic ideas in each interview through analytical categories and then distilling them into global concepts called codes. This is achieved in five stages. The first stage is a detailed reading of the transcript of the interviews, during which the main topics discussed by the interviewees in each intervention are summarised into analytical categories. These are keywords or phrases encapsulating the topic and perspective expressed by the participant. The second stage is to take all the analytical categories produced in the first stage and organise them into a cohesive system by summarising them into codes. Codes are a condensed version of the analytical categories applicable to all interviews. The relation and interactions between codes are defined at this stage too, giving rise to a constellation of codes (i.e., an interconnected system of codes). The third stage is to read the transcripts again and assign codes to each of the participant's interventions. The objective of this stage is to corroborate that the codes appropriately cover all the relevant topics discussed during the interviews. The fourth stage is a quantitative summary of the coding effort, i.e., to build descriptive statistics of each code frequency, their correlation, and other relevant numerical analyses. The fifth stage is using the constellation of codes to answer the research question(s). The first author performed all the interviews, as well as their main analysis. The second author validated the analysis by performing an independent analysis on a subsample of the interviews.

The main focus of our study was to identify the barriers and enablers of sustainability. To do this, we began by identifying, categorising, and creating a hierarchy of the main criteria used in manufacturing decisions. This allowed us to understand how each criterion acted as a barrier or enabler to sustainability. Therefore, the codes identified through this analysis ultimately correspond to different criteria used in manufacturing decisions.

As with any qualitative study, results cannot be generalised to the whole population of decision-makers in the manufacturing industry. Still, our results provide a deep and valuable understanding of the thought process of at least a subset of decision-makers in the manufacturing industry.

4. Results

In this section, and based on the analysis of interviews, the criteria identified as fundamental for making manufacturing decisions are presented. There are eight fundamental groups of criteria: *safety*, *quality*, *legal*, *cost*, *time*, *technical*, *sustainability*, and *supply chain*. Their relevance and relations can be better understood through a tree metaphor. *Safety*, *quality*, and *legal* are the essential requirements, without which any alternative cannot even be considered: they are the roots of the tree, as no tree can stand without roots. *Cost*, *time* (to implementation), and *sustainability* are the central criteria, which will often determine the choice: these are the trunk of the tree, shaping its strength and size. Finally, *technical* and *supply chain* criteria are the ones determining the technological and logistic details of each alternative, defining how strong the other criteria are, but themselves are composed of a large number of smaller and more specific sub-criteria with multiple trade-offs between them. They are similar to the branches of a tree: their leaves (sub-criteria) provide energy to the rest of the structure, but they can be pruned as long as the remaining branches and their leaves provide enough energy. Figure 1 summarizes these eight fundamental criteria, along with some of their most relevant sub-criteria.

In the remainder of this section, we will discuss each of the fundamental criteria in more detail, as well as their sub-criteria and how they relate to each other.

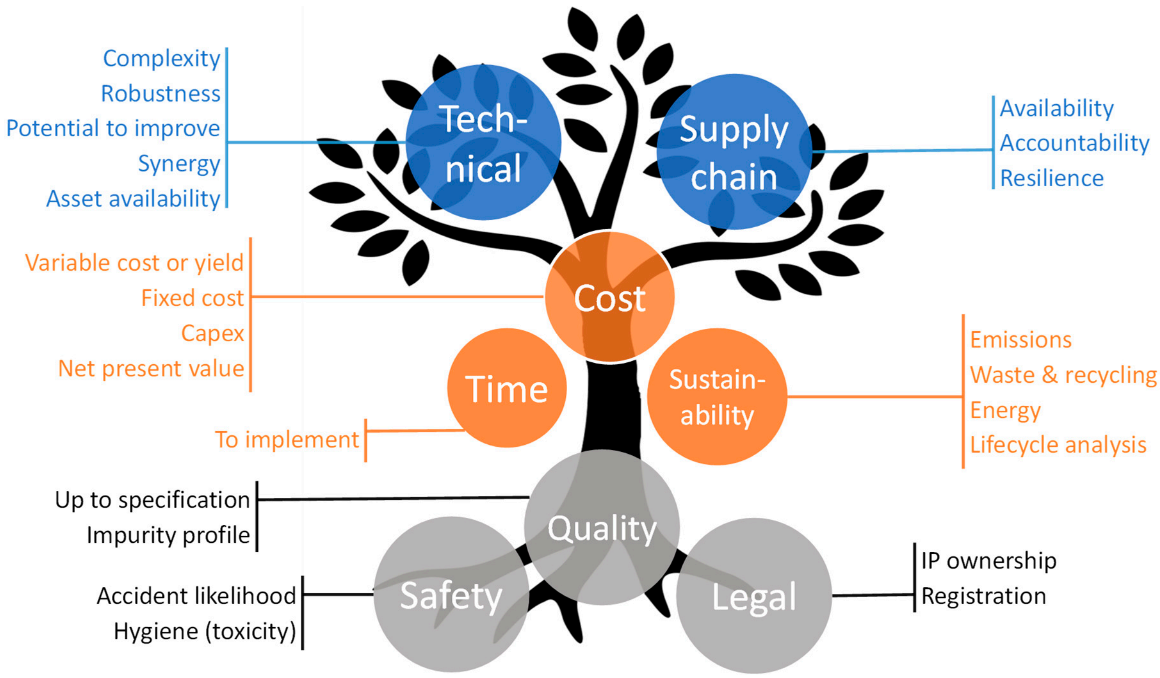

Figure 1. Fundamental criteria of manufacturing decisions.

4.1. Safety

Safety is an essential condition for any alternative to be considered viable in a manufacturing context. When discussing this criterion with safety experts, they highlight that no process (or alternative) is completely safe, but for it to be considered viable, the likelihood of an accident happening should be low enough. In practice, this translates into processes (or alternatives) to be dichotomously considered either safe or not safe enough.

> *I don't get involved if it costs £100 a kilo or if it costs £1000 a kilo. I don't care. What matters to me is: Have we got something which is safe, are we going to put anybody at risk if they carry out that chemistry?*
>
> *Interviewee S3*

The likelihood of an accident happening is hardly considered in a probabilistic way, but most often in a qualitative one. A process being safe enough depends on safety regulations (putting the safety criteria in direct contact with the legal criteria), safety guards, and the expected severity of an accident. Safety regulations will always have to be met and will depend on local laws. No process is considered a priori too dangerous to be performed, as safety guards can always be implemented. For example, explosive processes can be implemented by reducing the volume of the reagents, automating the process so no labourer is exposed to it, or reducing the temperature of the reaction to decrease the probability of ignition. Yet, all safeguards imply trade-offs with cost, implementation times, technical feasibility, yield, throughput, and potentially other sub-criteria. The severity of potential accidents is also considered when evaluating the safety of a process. To continue with the example of explosive reactions, using continuous reactors is considered safer, as the volume of reagents is lower, meaning any accident would not have major implications.

The *hygiene* or *toxicity* of a reaction is also a sub-criterion of safety. This relates mainly to the legal and sustainability aspects of the process. The main objective is to keep labourers safe but also minimise hazardous waste, while complying with all regulations.

4.2. Quality

Quality is also an essential condition for any alternative to be considered viable in a manufacturing context. Products must be produced to a specification, meaning that a process (or an alternative) that does not render the necessary quality of the product is not considered valid. This makes quality a dichotomous criterion. A process (or an alternative) either provides enough quality or it does not.

> *We have very little wiggle room on quality. Quality, I would say, is less of a concern, because if one of the two alternatives can't deliver the required quality, it's not an alternative.*
>
> *Interviewee S2*

Note that quality is independent from the yield or throughput. For example, consider process D, which has a high probability of producing defective items. As long as process D is capable of producing the required specification, then it fulfils the quality requirement. However, process D would require a large production run to obtain a given amount of non-defective products (when compared to a more reliable process), probably increasing the marginal cost of process A.

In addition to the need for the product to be up to specification, it is necessary to ensure that the production process does not generate undesirable side effects that make the product unsuitable. For example, consider the production of a chocolate bar through process F. This process is highly efficient but involves a high-temperature stage. This stage produces furans, an organic compound classified as possibly carcinogenic [45], and leads to an unacceptably high level of them in chocolate bars when the production line is in standard operation. Therefore, even though the product itself fulfils specifications when it comes to taste, aroma, and formula, its impurity profile (the residual components that were not part of the formula) is not acceptable.

4.3. Legal

Legal is the third and last essential criterion. Manufacturing is subject to legal regulations in every country. They include environmental, labour, safety, and potentially economic constraints that must be complied with. For a process or alternative to be viable, it must abide by all relevant regulations. These legal constraints must often be validated by an authority, making the production process less flexible, as any major modification often involves re-validating the process, which can be both costly and time consuming.

In addition to regulatory constraints on procedures, there can be additional legal hurdles to consider. In the case of chemical manufacturing, and potentially other highly regulated industries, each product must be registered with the local regulatory entity before commercialisation. This also makes production less flexible, as any modification of the production process may involve small modifications to the product, which require a new registration procedure.

> *Because if we have to change after registration and approval, it involves a lot of work to do that. And quite often the amount of different regulatory authorities in different countries have different rules and regulations about what they need.*
>
> *Interviewee S6*

Finally, both products and production processes can be subject to Intellectual Property (IP) protection. For example, a particular kind of reaction path (synthesis) can be patented, and therefore royalties must be negotiated and paid before using it. These legal aspects must be examined and solved before considering an alternative as viable.

4.4. Cost

Among alternatives that fulfil all the essential criteria, *cost* is often the decisive factor determining decision-making. Cost can be divided into four different sub-criteria: *variable cost*, *fixed cost*, *capital expenditure*, and *aggregate or net value*.

> *I name it only last but obviously, cost is the main driver.*
>
> *Interviewee S1*

The *capital expenditure* (capex) is the necessary monetary investment that allows production to start. It includes the investment in equipment but can also include investment in intangibles such as patents, licences, and even research and development. This expenditure is performed only once, at the beginning of the product's life cycle. Therefore, if the product is expected to be manufactured for a long time, the relevance of the capital expenditure is diminished; but if the product will only have a short life cycle, then capital expenditure is more relevant.

> *In this case as well, because it's a short period of time, what you look at mainly is the investment that you know it's your capex, the capital expense that you want to charge once to be able to produce a product.*
>
> *Interviewee S8*

Fixed costs are those costs that must be incurred every time a product is to be produced, but they do not directly depend on the amount produced. They include set-up costs for each run, the cost of labour, the depreciation of the equipment, the opportunity cost of using these resources for another activity, rent for land, etc. *Fixed costs* tend to be small in most of the manufacturing industry.

> *So we have the fix costs that are driven by the salaries obviously.*
>
> *Interviewee S1*

> *Actually, the fixed costs is the opportunity to do something, the variable cost is which we can influence.*
>
> *Interviewee S12*

Variable cost is the amount of money it costs to produce a single unit of product, and it is closely related to the *yield* of a process. While *variable cost* is expressed as GBP/unit and *yield* is expressed as unit/input, where the input is usually expressed as the volume or mass of input. But input can also be expressed in monetary terms as the total cost of the input, which is most convenient as it naturally gives more relevance to the most expensive inputs. By expressing input in monetary terms, we change the dimensionality of *yield* into unit/GBP. In other words, *variable cost* and *yield* are the inverse of each other.

If the product is to be manufactured in great quantity, or for a long time, the *variable cost* becomes the most important cost of all, as it tends to dwarf the other costs in the long term. However, when deciding on a new production line, the current *variable cost* may be misleading. It is assumed that throughout development, a production line will be optimised, driving the variable cost down. Furthermore, most companies work on a continuous improvement system, where the production line can be further optimised even after it becomes operational. This means that most decisions are based on the expected *variable cost* rather than the current *variable cost*.

> *How much can the active ingredient cost in the long term. Not for the pilot, [but] in the long term with a certain route, with a certain solvent, reagent, catalyst and so on.*
>
> *Interviewee S1*

The *net present value* is not another kind of cost but instead is a way of summarising all the other costs in a single value associated with the whole project or alternative. It is based on discounting future expected cash flows at a given rate, to calculate an equivalent present-day monetary value. While very convenient, inasmuch as it summarises all costs throughout the whole life cycle of the product, it is also difficult to calculate, as it requires knowing not only the expected sales of the product but also how costs might change in the future, so it is used very sparsely. Furthermore, if the largest contributor to the net value is known a priori (*capex*, *fixed*, or *variable costs*), then it is often easier to focus only on that component, as the net value will be driven by it anyway.

> *It's not like the company does everything which in theory has a positive Net Present Value (NPV). An NPV is a calculation, it's like you're trying to predict the future.*
>
> *Interviewee S11*

All costs are fully determined by other criteria. For example, the technical aspects will determine the amount of input required to manufacture a unit of product, while the technical aspects themselves are shaped by safety, quality, legal, and sustainability requirements. At the same time, the supply chain will determine the cost of raw materials. Therefore, the variable cost is a consequence of all other criteria and—in a way—summarises them. This explains why cost is usually the key criterion when making a manufacturing decision, once all the essential criteria (*safety*, *quality,* and *legal*) are fulfilled.

> *"Again, this is my minimal viable product scheme, and as I am in agro chemistry, cost, cost and cost are the three most important topics."*
>
> *Interviewee S12*

While *cost* is influenced by all other fundamental criteria, it leaves out any sub-criteria that cannot be directly measured in monetary terms. This is particularly relevant when it comes to externalities. For example, if the legal framework does not enforce payments for polluting, a focus on *cost* risks favouring more polluting alternatives. Other criteria that are difficult to value in monetary terms include impacts on the community and risks or uncertainties associated with other criteria.

4.5. Time

Along with cost, the *time* to implement an alternative or process is another decisive criterion. When deciding among different potential processes or modifications to implement, the amount of time it takes for them to be operative and in working conditions can be as important as the cost, or sometimes even more important. A typical example is during failures of the production line. If products are committed to clients but the production line is not working, then the main objective becomes fulfilling the order, even if that involves higher costs. This is because not fulfilling the order may have higher long-term costs, such as losing many future orders.

Time is often a decisive criterion in the pharmaceutical industry. This industry works under heavy regulation, and new products must go through multiple testing stages before reaching the market. Therefore, obtaining a quick approval of the first stages is often more valuable than an early optimisation of the production process. In other words, the pharmaceutical industry is often willing to use expensive production processes at the beginning of the regulatory process, as it knows it will have time to optimise the process and reduce its cost before the final registration of the product.

> *Decision is quite often driven on the timeline because we need to kind of meet the clinical timings; and then the cost will be kind of a next secondary issue.*
>
> *Interviewee S13*

4.6. Sustainability

The *sustainability* criterion is probably the one considered to have the least impact on decision-making among most of the interviewees. This is not because individuals believe sustainability to be irrelevant, the reality is quite the opposite, but mainly because sustainability measures are not easy to translate into monetary terms. As mentioned in Section 4.4, cost is paramount mainly because it constitutes an easy way to summarise all other criteria in a single dimension. Yet, as sustainability is not easy to measure in monetary terms, it is often not included in price calculations and therefore falls out of consideration. In line with this, several participants mentioned that sustainability is only considered when two alternatives have equivalent cost.

> *Sustainability for us, at the moment, comes in when we have two routes to compare, or when we have an obvious red flag. [. . .]. We are just currently building the real sustainability tools [. . .]. But historically, we are looking at costs, which is the cheapest route? Which is the cheapest catalyst? Which is the cheapest alternative? Assuming that we can safely produce it.*
>
> *Interviewee S1*

> *So, that's our first decision point: it is basically costs. These two routes were basically costing the same, which is not often the case. And they were really the same price. So then, we thought 'well what else can we look at' and we've been working a lot on sustainability recently. So, we did a very early life cycle assessment on the two routes. And our initial thought was that what we called 'alternative route', even though it was slightly more expensive, would be better in terms of waste, and in terms of sustainability.*
>
> *Interviewee S2*

Participants were well aware of sustainability being hard to consider due to it not having a clear translation into cost. In response to this, they expect imminent regulation on the topic, probably in the form of mandatory carbon pricing.

Finally, I expect there will be some ecology costs coming to all the companies. Whatever we do, we will be charged against the CO_2 value of some kind. I am pretty sure.

Interviewee S12

The expectation of a regulatory change in pricing pollution and environmental impact has led companies into developing more detailed approaches to sustainability. These translate into four sub-criteria: emissions, waste and recycling, energy, and life cycle or aggregate analysis. We discuss these next.

Emissions mostly refers to greenhouse gas emissions, especially CO_2. Some companies even have internal prices for CO_2, but they are still under development and are generally not yet considered in the cost estimation of an alternative or a new process. The general outlook is that reducing emissions is not an easy task.

In the world of chemical manufacturing I see a lot of companies, including our own, who -around carbon footprint- are kind of engaged with the debate. I think thermal energy would be a very difficult one to decarbonize, and our chemical waste. Because every carbon that goes into a chemical process and does not come [out] in the product that you want, will ultimately end up as CO_2.

Interviewee S7

Waste and recycling is probably the criterion that captures the most interest when making decisions, as it is the most closely related to cost. The more waste a process produces, the lower its yield and therefore the higher its cost becomes, because a big part of the inputs go to waste. Similarly, recycling allows reducing the amount of waste, as it allows the re-using of inputs, such as solvents and reagents. Furthermore, at least in the chemical industry, most waste requires different amounts of treatment depending on its toxicity, so reducing waste also helps reduce cost by minimising the amount of necessary treatment.

So, it always depends on what waste. Obviously, we want to have as little waste as possible. But there's tiers of waste. The waste we really don't like is one deriving from our starting material degrading or our product degrading, because that's direct money lost. Then you have the critical waste, the ones we cannot treat, the ones we cannot release, which are highly toxic.

Interviewee S2

The *energy* criterion relates not only to the total amount of energy used throughout the manufacturing process but also the origin of it. It directly relates to emissions, as all energy coming from fossil fuels directly adds to the carbon footprint of the process or alternative. Furthermore, the current energy crisis in the Western world has significantly increased the cost of energy, making this criterion have a clear impact on cost, therefore increasing its relevance.

Up until very recently (and I am as guilty on this as anybody) the cost of energy was just something that was at the end of the pipe. And sort of there when we needed it. [. . .] And we might only look at energy consumption when at year 20 of the life cycle, when looking into optimisations. I think when we are in the very early part of a product life cycle, we should be thinking about the whole process, you know: the waste, and the energy consumption. And not just in phase one manufacture, [. . .] but how will this look when you're at phase two manufacture, which is very likely to be in China, where the actual labour cost is very low, but energy costs dominate.

Interviewee S7

The *life cycle analysis* criterion relates to a more integrated sustainability analysis performed by some companies. It involves assessing the full environmental impact of a process, including the impact of raw material extraction, transportation, manufacturing, waste generation and treatment, energy generation, and others, up to the point where the product is out of the manufacturing facility. This approach is recognised as clearly superior, as it encompasses all other sustainability sub-criteria and summarises them in a clear way. Yet, it is very difficult to implement because (i) it requires massive amounts of information (e.g., emissions throughout the whole supply chain), and (ii) the methodology to weight, harmonise, and consider different types of environmental impacts is not clear. Concerning the last point, most current life cycle assessments focus on greenhouse gas emissions because there is a clear way to calculate equivalent CO_2 emissions for multiple sources. However, it is not always clear how other kinds of environmental impacts (e.g., soil degradation) fit into emissions. Finally, even if all impacts could be translated into equivalent CO_2 emissions, there is still no globally agreed-upon price for CO_2. Nonetheless, most interviewees agree that life cycle analysis will be the standard methodology to assess environmental impacts in the future.

> *And we are moving now to what we call a life cycle assessment. Which actually, we still don't really know how to measure it. [...]. That question has yet to be asked in a serious way. This company, it's moving towards that. But I think people much more senior than me are going to have to start making some fairly hard decisions.*
>
> *Interviewee S6*

Finally, the *social* aspect of sustainability was only tangentially mentioned throughout the interviews, never as a component of sustainability but instead associated with safety (wellbeing of workers and consumers of the manufactured product), *legal* (respecting labour laws of employees), or *supply chain* aspects (no slave or child labour throughout the supply chain).

4.7. Technical

Technical criteria may not be the most highly regarded aspects when making a decision, but they are largely the ones determining all other fundamental criteria. Technical aspects will determine the safety of the process (at least before imposing additional safety measures), the quality of the product, and the potential regulatory and intellectual property legal issues. The cost and time of implementation are almost completely determined by technical aspects. The technical aspects of the production process determine sustainability to a high degree before implementing recycling and waste treatment. Only supply chain criteria are exogenous to the technical aspects and condition them.

Technical criteria are the ones determining all technological aspects of the production process or its modifications. At a very low level, it includes a large group of sub-criteria, from the kind of technology used (e.g., batch or continuous reactors) to operation conditions (e.g., the operating temperature of a reactor). We organise these sub-criteria into five main groups, which we discuss next.

The *complexity* sub-criterion refers to the intricacy of the alternative or the process under consideration, and therefore to how difficult it would be to implement it. Making an alternative work as expected can be difficult due to engineering issues or because additional research and development are needed. Complexity is relevant because investment is often needed before the alternative viability is fully determined, so investing in an overly complex alternative is riskier.

> *Could we operate [a technically complex but low-cost chemical process]? So did we have enough technical confidence in the lower cost option? Or are we going to think 'well you know what, this product is so valuable that we don't want to take a risk of getting it wrong', constraining ourselves.*
>
> *Interviewee S7*

The *robustness* sub-criterion relates to how prone or resistant to failure the process or alternative is. Assuming that the alternative or process can be implemented, this sub-criterion considers how often it is likely to fail, and in the event of a failure, how easy it is to solve or circumvent the problem. This sub-criterion measures the risk or uncertainty associated with an alternative's performance.

> *This is more or less what we call the process robustness. If it's always working fine it's robust. If you do a slight change and you have huge impacts, then that's certainly not robust.*
>
> *Interviewee S11*

The *potential to improve* is a relevant sub-criterion inasmuch as many manufacturing decisions are taken with incomplete information, so it is expected that a given alternative can be further optimised even after deciding to implement it. Furthermore, many manufacturing companies work under a continuous improvement framework, meaning that a process can be further optimised even after its implementation. Improvement can be measured in many different dimensions: reduced variable cost, increased throughput, reduced emissions, etc.

> *You know, when we produce a good product with good tonnage, then we can spend also the engineers and chemists [time] to optimize even further and further. If it's a small product, just a few hundreds of tonnes, then it's difficult to allocate too many people so it's also volume bound.*
>
> *Interviewee S12*

The *synergy* sub-criterion relates to the capacity of a process or alternative to provide additional benefits beyond its main manufacturing objective. This is especially relevant for capital investment, where the machinery necessary to implement one line may be flexible enough to use in other tasks.

> *I guess to simplify the discussion you can consider it as building a scale of Lego bricks, you know, with many different colours of bricks. And the colours of the bricks aren't going to change [across scales], but what makes the scale is the order and number of bricks that are stuck together. So when we see a project come along that we call a platform capability (and we've had a couple of those), we invest in the platform and will kind of say "right, we're going after these drugs, we need these bricks in six different colours". Let's do that exercise on each one of these bricks and get really, really efficient. Then for every other project that comes along, we have a big stack of the bricks we can put together.*
>
> *Interviewee S13*

The *asset availability* sub-criterion refers to the possibility of using the necessary machinery and resources to implement the considered process or alternative. In many manufacturing plants, at least some resources are shared between production lines or processes. For example, the same machinery can be used to manufacture two or three different products. If a new product wants to be manufactured with the same resources, then it is necessary to ensure that they will be available.

That also factors in things like what other products [we are making]. So we're a multi-product site. So, what other products are manufactured on the other lines? which lines are going to be free? which ones can be more available? Because it's no good us activating a line that is currently chockablock with another product that we can't unpipe.

Interviewee S5

All these sub-criteria depend on, and are shaped by, more specific and detailed underlying criteria, such as the kind of technology used, operational conditions, size and location of the production line, production schedules, etc. However, the highly specific nature of these underlying criteria makes them unsuitable for use during a high-level decision-making process. Therefore, only the consequences of the underlying criteria, namely the *complexity*, *robustness*, *potential*, *flexibility*, and *availability* of the alternative, are considered during the decision-making process. Furthermore, underlying criteria are often set to the optimal values given a set of constraints, so their values are not relevant for the decision-making process. For example, the operational temperature of a reactor is such that it maximises the efficiency of the reaction inside while abiding by safety regulations. Hence, there is no reason to consider an alternative with a lower or higher temperature, meaning that the temperature is not a relevant criterion when choosing among a set of alternative processes.

4.8. Supply Chain

The *supply chain* criterion groups elements related mainly to raw material providers and outsourced work, both for outsourcing particular stages or waste treatment, as well as outsourcing the full manufacturing process. Supply chain aspects have gained increased relevance in the last few years for two reasons. First, the COVID-19 pandemic proved that worldwide supply chain shocks are not only possible but can also develop extremely quickly, generating disruption even in supply chains that used to be considered robust. Secondly, recent world events are quickly causing a decoupling of Western and Eastern economies, with an increasingly disruptive trade war between the US and China, and an energy crisis in the West due to the war in Ukraine. Associated with this economic decoupling is a political polarisation of international relations, which can further cause disruption in international supply chains.

Instead of listing all the possible risks and characteristics that a *supply chain* can have, we disaggregate the supply chain criterion into just three sub-criteria. This allows for greater flexibility when applying the taxonomy to different manufacturing problems. These criteria are *availability*, *accountability*, and *reliability*. While each represents a different dimension of the supply chain, they are intrinsically intertwined, as discussed in the following paragraphs.

Availability represents how easily available a resource is. Or in other words, from how many providers can a product (e.g., raw material) or service (e.g., waste treatment) be sourced? Availability has a direct bearing on the cost of sourcing, as high availability means more competition, making it easier to negotiate a favourable procurement price. Furthermore, availability can determine the feasibility of alternative processes, as, for example, some raw materials simply cannot be procured at the necessary volume when production is scaled up.

Are the reagents and the raw materials available on bulk? Do we have to buy the world production of rhodium?

Interviewee S1

The *resilience* criterion relates to how easy it is to overcome issues in the supply chain of the alternative or the process under consideration. It potentially involves many different aspects of the supply chain design and characteristics, but two aspects were most often highlighted by the interviewees: the level of confidence in the supplier, and the hedging of risks. The level of confidence has to do with how close of a relationship the client has with the supplier: have they worked together before? Are both parties' interests aligned? Does the supplier have a history of fulfilling obligations?, etc. A higher level of confidence in the supplier can imply a willingness to pay a premium on the procurement price.

> *When we come to select a commercial manufacturer, we have a group of what we call frontline manufacturers, who will usually be European rather than outside of Europe. So they are the closest manufacturers, but it's the most trusted ones, with whom we already have significant background experience, and there are about half a dozen. Now, the list does change.*
>
> *Interviewee S6*

The second aspect of *resilience* is risk hedging. A given supply chain set-up may be prone to disruption, but this does not constitute a serious problem if there are contingency plans in place. In other words, if risks are hedged, then a supply chain can be considered resilient. This usually implies sourcing materials or services from multiple providers so that if one fails, another can cover for the failure. However, the mere presence of multiple providers is not enough to guarantee high availability, as many of them could rely on a single (or a handful) of providers down their own supply chain.

> *So normally we mitigate this risk by having multiple suppliers, so by not having all eggs in one basket. So normally, we look at one supplier [from the] East [and] one supplier [from the] West. The West is more expensive, more reliable. The East is a better financial opportunity. And this is the ideal case. Or multiple suppliers in the East, where we can say "Oh, these are independent". But then the second question you should ask is "Are they really independent?" You find out when there's a closure of a production site in China, and you see how the supply chain collapses by finding out that both contractors you had, east and west actually relied on the same source. And, in some raw materials, nowadays, this is a huge worry, and we have started to dig into the supply chain of the supplier, if possible. To see whether we have some common risks.*
>
> *Interviewee S12*

Geopolitical issues play a significant role in the resilience of a supply chain as well.

> *If you have China and China's allies, and the western world with the US and their allies end up with trade wars, with embargos. [. . .]. The world depends so much on China. But if we get lots of tariffs and trade barriers, would you want to be fully exposed to China? And how would India respond to that? Because in our world of chemical sourcing, it's India and China, and also Europe. So, Is India going to align with the Western world, or is it going to align with China? I don't know the answer to that.*
>
> *Interviewee S7*

Accountability is the final sub-criterion of the supply chain. This sub-criterion mainly relates to social responsibility throughout the whole supply chain. Similarly to sustainability concerns, accountability is hard to translate into monetary value, often having little or no impact on cost. This reduces accountability's relevance in the decision-making process. Given this reduced impact, accountability is often reduced to the most fundamental checks, such as making sure that providers abide by safety measures and minimal labour regulations.

We need to make sure that none of our base chemical sources has been made by companies that are either exposing people, exploiting employees, having child labour, or polluting the environment. And once you have that duty of care, you need to think back, think about where's this coming from? who's making it? how are they making it? and send the auditors back.

Interviewee S13

4.9. A Note on Risk, Uncertainty, and Demand

We do not list risk or uncertainty as additional criteria in our taxonomy (see Figure 1) because there is risk and uncertainty associated with all criteria. In other words, risk and uncertainty are not criteria by themselves, but they represent variability associated with each criterion discussed.

An adequate decision-making process should take into consideration the variability expected in all criteria. Summarising the variability of all criteria into new artificial criteria called risk or uncertainty would not represent the nature of the alternatives correctly, as the consequences of variability in different criteria can differ widely. For example, a higher-than-expected cost can render a project moot, while the failure of a raw material supplier could be overcome easily if the raw material has high availability. Considering uncertainty independently for each criterion allows for a sensitivity analysis or for evaluating different scenarios.

The most difficult part in my mind is dealing with the uncertainty. [. . .]. My product volume target may change, or my sourcing structure may evolve and change. That will have a dramatic impact on my parameters [(criteria)] but, importantly, on which ones? [. . .]. And what you've really got to do is understand what's the sensitivity between them. [. . .]. I would like to have the ability to predict the likelihood of my different scenarios playing out, and that's the most difficult thing. [. . .]. We need to understand what impact that will have on our decision, and so I think that's the hardest thing to deal with.

Interviewee S9

Concerning demand, interviewees considered it an exogenous factor for the decision-making process. In other words, demand constitutes a constraint, not a criterion. Demand is seen as a production amount that needs to be fulfilled, not a characteristic of the process or alternative. However, they do acknowledge that demand forecasts are often wrong, so an alternative or process that is robust and scalable is always desirable.

Usually, our forecasts on demand are invariably wrong. It's guesswork.

Interviewee S6

5. Discussion

The analysis of the interviews produced a clear hierarchy of criteria for manufacturing decision-making, with three tiers. The first or "root" tier is a set of criteria that must be satisfied to an acceptable minimum for an alternative to be considered viable. At the same time, there is little perceived benefit in going over the acceptable minimum. This tier includes three criteria: *safety*, *quality*, and *legal*. This means that any process or alternative under consideration must have an acceptably low likelihood of accidents, it must be capable of manufacturing the product up to specification, and it must fulfil all necessary regulations and legal requirements.

The second or "trunk" tier of criteria comprises *cost*, *time*, and *sustainability*. These are the most relevant aspects when making a decision. *Cost* has at least three sub-criteria: capital expenditure, fixed cost, and variable cost, with the latter often being the most relevant one for products that will be manufactured for a long time. The *time* criterion relates to the amount of time it takes to implement the alternative or process. Depending on the industry and stage of the development, cost or time can be more important than the other. Finally, *sustainability* is the least relevant of the three trunk criteria and encompasses four sub-criteria: emissions, waste and recycling, energy, and life cycle (or other aggregate) analysis.

The "trunk" tier of criteria is essentially a summary of the other two tiers of criteria in the sense that decisions related to all other criteria completely determine the cost, time, and sustainability of an alternative. This makes *cost*, *time,* and *sustainability* very useful indicators for the overall attractiveness of an alternative. However, as with any summary, information is lost. *Cost*, *time,* and *sustainability* explicitly or implicitly give the other criteria different weights. For example, in the case of *cost*, anything that does not have a market price will be ignored in the *cost* criterion, while anything with a high price will dominate the *cost*. Therefore, while useful, decision-makers should be aware of the underlying assumptions behind the trunk criteria of an alternative.

The third or "branch" tier of criteria includes more specific criteria and sub-criteria, underlying most of the details and attributes of the alternative or process. There are multiple trade-offs between these criteria, and improving one criterion will often imply worsening another. These criteria are often the main differentiators between alternatives, as they define their technological and logistic characteristics.

A notable absence in the proposed structure is social or community-oriented criteria. The classic three pillars of sustainability [6] include economic, environmental, and social criteria, with the latter being associated with the impact of manufacturing on both labourers and the larger community. In our analysis, we only found the social aspect to be partially reflected in *safety* (the manufacturing process must be safe enough for labourers) and *legal* (the manufacturing process must comply with local labour regulations). Beyond that, there were no mentions of the impact of manufacturing on the community, except for the bare minimum, e.g., ensuring that there is no slave or child labour in the supply chain. However, we observed no mention of the people living close to the manufacturing plant, the labour conditions of external contractors, or even the work security of their own employees, except for one mention that labour costs are sunk because employees are not terminated if a particular production line is closed. This finding is in line with the reports of [28,29,32,36] and contrasts with the much broader definition of social sustainability by [46], which encompasses labour practice/working conditions, diversity and equal opportunities, relations with the community, social policy compliance, safety and health, customer satisfaction, product responsibility, and education.

Based on the information collected through the interviews, the cost criterion seems to dominate most decision-making in the manufacturing industry. This is in line with findings from [29,32]. As mentioned before, cost, time, and sustainability are fully determined by all other criteria, so they can be perceived as a summary of an alternative's characteristics, and as such, decision-makers tend to focus only on these criteria. At the same time, cost, time, and sustainability are measured in very different units, without a clear trade-off between them. Cost and time have clear units of measurement and are easy to communicate and evaluate: lower costs and faster implementation times are always preferable. In some industries, delivery times may be more relevant than production costs, while in others, costs are more important; but it is often possible to assign an equivalent cost to delays, so trade-offs between the two are relatively straightforward. On the other hand, and according to most interviewees, there is not even an agreed standard to measure sustainability, which itself is multidimensional. For example, it is not always clear if reducing carbon emissions or the use of a toxic solvent is preferable. And even if a single measure of sustainability were used (e.g., tonnes of equivalent CO_2 emissions), there is no agreed trade-off between it and cost and time. This difficulty in measuring and valuing sustainability often causes decision-makers to focus on cost and time as the key decision drivers, relegating sustainability to a second tier of importance.

There are some aspects of sustainability that are regarded more highly by decision-makers, namely reducing waste and energy consumption. The reason for their higher relevance is that they have a direct impact on cost: reducing waste implies paying for less waste management, and reducing energy consumption reduces the variable cost of production. This reinforces the idea that as long as sustainability does not have a clear measurement unit, and a well-established trade-off with cost, it will be relegated to a second tier of importance. This explains why emissions and social aspects of sustainability have low relevance in the hierarchy of criteria: it is because they can hardly be valued in monetary terms.

In terms of the main barriers to sustainability in the manufacturing sector, our results largely match those found in the literature. Interviewees agreed that there is a lack of standardised measurements of sustainability [25,26,28], which can make the comparison of sustainability levels across alternatives and across time difficult. Related to the previous point, many interviewees mentioned a lack of a holistic approach to sustainability [22,23,39], and though life cycle analysis is a promising answer to this need, they also mentioned that it was difficult to implement and still under development in their organisations, even though there are agreed international standards for it, such as ISO 14040 [47]. This lack was also reflected in the need for new decision support tools capable of considering sustainability from such a holistic approach [22,35,36], which interviewees claim would help them make and communicate decisions more easily. Finally, interviewees also agree with sustainable manufacturing processes lacking economic incentives to be implemented [11,13,30], as they claimed that the most sustainable alternative was only chosen when it was not more expensive than a similarly productive but less sustainable alternative.

6. Conclusions and Recommendations

Based on the thematic coding analysis of 15 narrative interviews with decision-makers in the chemical manufacturing industry, we identified three main barriers to sustainable manufacturing:

i. A lack of standardised measures of sustainability. Sustainability is a multidimensional construct, and there is no standardised way to measure it, at least in industry. This makes the comparison of sustainability levels difficult across alternatives and time and makes trade-offs against other criteria difficult to define.

ii. A lack of a holistic approach to sustainability. As there is no standard way to measure sustainability, it is not easy to optimise it across different stages of the production process. While there are promising approaches to this (life cycle analysis and circular economy, among others), they are not yet implemented in industry.

iii. A lack of economic incentives to implement sustainable manufacturing technologies. Sustainable manufacturing processes are often more expensive than less sustainable alternatives with similar yield performance. As greenhouse gas emissions and other negative environmental externalities are often not taxed or assigned a monetary value, there is little economic incentive to implement them.

While the most mentioned barrier to sustainable manufacturing is the lack of economic incentive, all three barriers are closely linked. Implementing economic incentives (e.g., taxes) would require defining a standard way to measure sustainability across each stage of the product life cycle so that an appropriate externality cost could be calculated. Furthermore, a sustainability measurement that generates enough consensus to become standard would inevitably call for a holistic approach, integrating economic, environmental, and social factors.

However, until a price for sustainability is agreed on, an alternative way to promote sustainable manufacturing is using decision support systems that facilitate the consideration of non-monetary criteria, hence allowing for easier and more transparent trade-offs between costs and sustainability. Multiple criteria decision analysis (MCDA) techniques are promising candidates. These techniques break down complex decisions into multiple smaller and simpler ones, which are then used to infer the best alternative in the larger and more complex decisions. Several of these techniques, such as the weighted sum method [48], Analytical Hierarchical Process (AHP) [49], Multi-Attribute Utility Theory (MAUT) [50], or SURE [51] can even derive measurable trade-offs between criteria, potentially allowing for the calculation of explicit monetary values for sustainability, which are dependent on the context, particular application, and preferences of the decision-makers.

MCDA matches the expectations of what a useful decision support tool should be, according to the participants of the study. It is flexible, allowing for the consideration of different criteria depending on the project or decision at hand. It allows for the inclusion of uncertainty in outcomes and criteria. And it provides an easy way to explain and justify a decision to other decision-makers who may not be experts in a particular technical field (e.g., it helps a chemic explain a decision to a business manager).

As with most research, this study is limited by its sample. The sample is relatively small (15 individuals), and while it includes contributors to decision-making from both the specialty chemical and pharmaceutical industries, it is biassed towards the former. Furthermore, only one interviewee is not based in Europe, which limits our results in terms of geographic representation. Despite this limitation, the analysis rendered a wide range of criteria and barriers to sustainability that compare favourably with the ones reported in the existing literature.

Further work is necessary to develop, test, and implement decision support tools that can promote sustainable manufacturing by increasing the relevance of sustainability in the decision-making process and propose transparent ways to trade it off with costs. Quantitative studies exploring the effects of these methodologies on overall emissions and other sustainability measures are also critical to provide robust policy recommendations.

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Abbreviations

The following abbreviations are used in this manuscript:

MCDA	Multicriteria Decision Analysis
UN	United Nations
LCA	Life Cycle Analysis
CE	Circular Economy

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