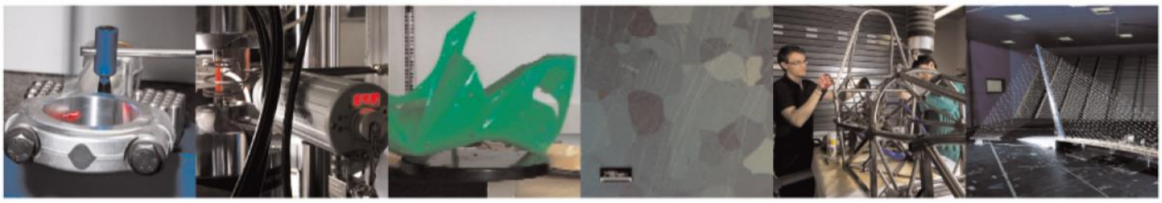

Assessment of valorisation opportunities for secondary metallurgy slag through multi-criteria decision making

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Assessment of valorisation opportunities for secondary metallurgy slag through multi-criteria decision making

Abstract

This paper analyses the valorisation opportunities for the secondary metallurgy slag (SMS) as a by-product of electric arc furnace (EAF) steel production. The Analytic Hierarchy Process (AHP) has been adopted to evaluate the important criteria, namely technology, legislation, economic and environmental sustainability, and supply chain within the SMS value chain. The multi-criteria combined with the multi-expert modelling approach helps balance the importance of different criteria from the actors' points of view, such as steel producers and technology providers. To build the model, we identified the key stakeholders, their aim and potential added value to valorise the SMS value chain. The results show economic sustainability has the highest importance, while CO_2 emission and water consumption are other sub-criteria that significantly impact the SMS value chain.

To analyse the impact of circular economy practices and the opportunities for industrial symbiosis in the European steelmaking areas, alternatives considering the treatment unit owners and locations, pre-treatment and treatment processes, and collaboration aspects have been defined. For validating the model, the Lombardy region as one of the major European hubs for EAF steel production has been selected. Alternatives' ranking shows that a pre-treatment phase is essential since it facilitates SMS logistics management and has environmental advantages. A collaborative approach among steel producers or external recyclers is preferred when there is the readiness of the ecosystem, hardware infrastructure, product certificate and operations legislation. In a collaborative system, a third-party recycler is preferred to a consortium of producers collaborating for slag recycling due to the broader market coverage, environmental sustainability, and higher profits for the recycler. This study can be helpful for steel producers to decide on the feasibility and profitability of establishing treatment units, collaborating with other producers, or selling SMS to recyclers. It can also be helpful for policymakers to analyse the regional perspective and potential industrial sectors and explore new business models.

Keywords: Secondary metallurgy slag, value chain analysis, circular economy, analytic hierarchy process (AHP)

Abbreviations:

EAF: electric arc furnace; SP: steel producer; TU: treatment unit; SMS: secondary metallurgy slag.

1. Introduction

The outlook of steel industry's future for the next 30 years pays particular attention to the research and innovation in feedstock valorisation, smarter use of cross-sectoral technologies and new applications, aiming at avoiding, valorising, and reusing waste streams (Spire roadmap 2030). Among the strategic objectives set out by the European Steel Technology Platform (ESTEP, 2017), there is a particular focus on ferrous slag as the second critical material, after scrap, in the steel circular economy to maximise the valorisation of the steel by-products in a local economy.

To produce high-quality steel, the liquid steel produced by electric arc furnace (EAF) is used in secondary metallurgy (ladle furnace), where the fluxes, such as lime and dolomite are combined with the melted steel and form the slag on top of the furnace. Secondary metallurgy slag (SMS) is typically formed as white powder material after cooling. The properties and chemical composition of SMS differ according to steel producers' (SP) steel types and casting processes. The heterogeneity of the raw materials used in the furnaces causes the necessity of a chemical quality check for the SMS treatment, resulting in higher production costs and time.

Several studies have analysed the SMS value chain to explore the opportunities for industrial symbiosis and circular economy. However, the following gaps can be identified:

- The studies in the literature lack a holistic approach where all crucial factors are considered.
- The focus of most studies of such systems is on the primary stakeholders, i.e., SPs, without considering the role of others, such as policymakers and potential new entrants into this business.
- The studies investigating the role of stakeholders and technological advancements in collaborative ecosystems typically do not consider the impact and feasibility of treatment processes in multiple layers within the supply chain.

In this paper, we tackle these gaps by proposing a framework to analyse the SMS value chain with the aim of valorising it while preventing landfilling. To this aim, innovative business models are proposed, focusing on closed-loop value chains and sharing knowledge and best practices. These business models facilitate the deployment of R&D opportunities and reach out to influential stakeholders, such as policymakers and investors, to support the full implementation of specific actions (Li et al., 2022).

SMS treatment can potentially be carried out in two phases in the supply chain. Some treatments can be carried out uniquely either by the SPs (e.g., cooling methods) or by industrial users, while other treatments can be technologically performed by both parties. In addition, a set of product mixes from slag treatment can be obtained within a value chain of different SPs. From a strategic viewpoint, this diversity affects the economic and technological aspects, and from an operative viewpoint, it affects the production and selling volumes of product mixes. We model this complexity within the circular economy approach through a systemic perspective in which the integration of existing production infrastructure for the recyclers and the market acceptance of recycled products for the use-oriented businesses are key enablers (Tolio et al., 2019).

The industrial symbiosis approach is considered in this work to address the slag's economic and environmental challenges and manage the use of cross-sectoral technologies (Branca et al., 2021). SMS use in different industries benefits both SPs and customers. Specifically, SPs can decrease landfilling costs and meet environmental regulations against slag stockpiling (Xue et al., 2022), thus potentially reducing the selling price of raw materials for user industries while preserving natural resources. This approach requires a strong collaborative network among the stakeholders to foster the synergies of the slag flow within the supply chain.

The contribution of this study is to exploit SMS for different treatment activities, coping with high economic and supply chain complexities in the ecosystem. Another contribution is that the results facilitate decision-making for policymakers with influential roles in the regulatory aspects, collaboration with industrial organisations, and incentivising authorities. A proper legislative framework in the steel sector results in sustainable development and appropriate functioning of the internal market (European Commission, 2013).

After the literature analysis (Section 2), we address the SMS features and define the problem and the role of stakeholders (Section 3). Then, we propose a framework to support decision-making by structuring the challenges into multiple criteria and feasible options. This approach is based on the Analytic Hierarchy Process (AHP) and takes advantage of the knowledge of domain experts (Section 4). The approach was tested in the case of SPs in the Lombardy region of Italy (Section 5). Finally, we conclude by discussing different alternatives and prioritising the identified criteria for a winning SMS value chain (Section 6) and possible research directions (Section 7).

2. Literature review

In this section, we analyse the relevant studies related to the value chains in industrial symbiosis, waste management, and new product development to find the best modelling approach for solving the challenges in the SMS value chain.

Principal factors investigated by the models in the literature are the economic and environmental impacts. Wen et al. (2017) and Zhang, Dong, et al. (2013) focused on minimising total investment and operating costs of technologies in iron and steel ecosystems. Wen et al. (2017) used single-objective optimisation equations and analysed energy savings and cost-efficiency. Zhang, Dong, et al. (2013) used substance flow analysis to evaluate the carbon mitigation in iron and steel industrial parks.

In the iron and steel industries, Mahjouri et al. (2017) analysed the optimal wastewater treatment technology, considering system complexity and economic and environmental impacts. They used a multi-criteria decision-making approach based on AHP and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Considering the sophisticated judgments among the challenging criteria, their methodology uses experts' opinions to tackle it. To analyse the intangible criteria in AHP, Monitto et al. (2002) used fuzzy evaluation and analysed the uncertainty of market and technology to select the best automated manufacturing system.

Cimren et al. (2011) and Cao et al. (2020) minimise total costs and environmental impacts through mixed-integer programming (MIP). Cao et al. (2020) analyse the ecosystem of the iron and steel industries, the cement industry and the thermal power and propose suggestions for technology implementation and the materials exchanges that can be discouraged and encouraged in such an ecosystem. Cimren et al. (2011) represented the impact of their study on ecosystem profitability, cost reduction, CO_2 emission reduction and landfill reductions.

On the steel by-product valorisation, landfilling prevention is another influential factor in the models. Larsson et al. (2006) evaluated the energy and material efficiency of the main solid by-products (slag, dust, and sludge). Their objective was to minimise the landfilling volume and maximise internal recycling through a joint process integration model. The objective of Lundkvist, Larsson, and Samuelsson (2013) was also minimisation of landfilling volume on dust and sludge. However, their mixed-integer linear programming (MILP) model aimed at tactical decisions by considering the material supply, storage, and transportation frequency.

Matino et al. (2017) instead focused on the economic objectives of sludge and slag to minimise steelmaking and treatment costs, as well as maximising the internal recycling. Helle, Helle, and Saxe (2011) had the same objective by focusing on gas emissions as the steel by-product. Tang et al. (2008) assess the selling income in addition to the costs and maximise the profit of the steel waste through a MIP model, considering the recycling and treatment strategies and the production volumes. Analysing the application of steel slag resources, Kang et al. (2018) used AHP modelling to evaluate the economic feasibility, resource suitability, and environmental acceptance. This model proposed recommendations for the sustainable development of steel enterprises and recycling resources.

Although practical and theoretical evidence confirm that the SMS value chain requires new configurations and business models, the literature lacks a holistic approach where in addition to economic and environmental analysed principally, other characteristics, such as supply chain and legislation, should be integrated in a unique model. A potential model analysing these criteria should be capable of handling different value chain scenarios where some may have contradictory influences. For example, advanced technology for slag treatment and a high potential for collaboration among SPs result in more collaborative solutions. In comparison, logistics challenges may lead to more independent slag treatment solutions.

Furthermore, symbiotic collaborations should be investigated in different aspects beyond a purely economic analysis, also considering the actors' roles and benefits towards business opportunities, network inequalities, and regulatory aspects (Harfeldt-Berg et al., 2022).

3. Materials and methods

This section addresses the SMS characteristics that motivate the necessity of new value chains by emphasising the role of pre-treatment processes (Section 3.1). Consequently, the role of actors in this value chain is discussed (Section 3.2).

3.1. SMS features

By combining fluxes and alloys in the ladle furnace, steel is desulfurised, and high-quality steel is produced employing electric energy and argon gas. SMS, as the main by-product of this process, consists of a high proportion of lime (CaO) and Silicon oxide (SiO_2) and a low proportion of iron content (FeO) (Yildirim and Prezzi, 2011). Lime is used to purify the steel by removing aluminates, silicates, sulphur, and phosphorous. The mineral analysis of steel slag indicates that Olivine, Merwinite, C_3S, β-C_2S, C_4AF, C_2F, RO phase (CaO–FeO–MnO–MgO solid solution) and free-CaO are common (Shi, 2002). Although SMS has a high content of CaO, only a proportion can be reacted in combination with other materials (Kriskova et al., 2012). The main mineral in air-cooled ladle slag is C_2S and is in the phase of α- C_2S when it is melted. SMS has fine particles due to the conversion of β-C_2S (at 630 °C) to γ-C_2S (lower than 500°C) during the cooling process (Memoli et al., 2007), which has less density. This conversion causes a volume increase of about 12%, known as the dusting phenomenon (Iacobescu et al., 2016).

The dusting phenomenon and the volume expansion result in difficulties in slag handling and transportation in the as-received form, in turn increasing the supply chain costs. Therefore, the decision on the slag treatment and its market is a trade-off between the technological possibility of different SMS types for internal use and the economic balance with its use in other applications.

Three challenging issues hinder the application of SMS, distinguishing it from the other slag types (Radenović et al., 2013; Skaf et al., 2016):

1. Volume instability of the mix: Due to the high proportion of lime, the direct use of SMS without any treatment is challenging.
2. Volatile composition of slag based on different steel grades, input materials for EAF (i.e., scarp), the fluxes in the ladle furnace (e.g., lime and dolomite), and in some cases, cooling practices.
3. Exposure to the stockpiles: results in powder formation and makes it difficult to handle and transport.

These challenges bring opportunities to a wide range of slag treatments and applications in various industries, such as SMS use as geotechnical fill material (Yildirim and Prezzi (2017)) and feedstock for EAF (Guzzon et al. (2007)). We can define the principal processes in these studies as SMS "treatment" and define them as processes in which the final product can be directly used in the user industries as feedstock. Any handling activity (e.g., slag transfer from the furnace) is excluded from this definition since they are considered common practices (European Parliament and Council, 2018). However, SMS can undergo an initial phase to be prepared for the treatment process. We define this initial phase as "pre-treatment", which adds value to the slag, but the final product cannot be used directly in other industries and needs further treatments.

A pre-treatment can be performed inside the steel production plant either before or after the cooling process, or in an external treatment unit (TU). An example of a combination of these pre-treatments is the ultra-fast cooling by utilising an industrial fan located at the exiting point of the slag pot and a screen for metal separation, preventing the SMS from slow cooling and the consequent powder formation. After this pre-treatment process, the amorphous structure of the SMS facilitates the dust handling issue. Compared to the traditional wet granulation method, this dry granulation method has the advantage of low water use, easy setup, possible heat recovery, and no contact with another surface. This technology is under initial implementation and is being tested in some companies in Italy. It does not have a high production rate and requires the training of operators (Guzzon, 2020).

3.2. Problem statement

Based on studies in the literature (Section 2) and the SMS features (Section 3.1), an analysis of the value chain is needed to address the valorisation of SMS and assess the role of different stakeholders. In particular, based on interviews with the main stakeholders in the field (SPs, technology providers, and associations) and a previous study (Falsafi and Fornasiero (2022)), we propose the SMS value chain network in Figure 1 and define the relevant stakeholders in Table 1.

The role of TUs is relevant for designing new value chains aimed at valorising high-volume landfilled SMS. A TU is a facility with an infrastructure devoted to the recovery activities on slag, regardless of its type and location within the slag value chain. The recovery activities can be a company's main business (i.e., SMS treatment company), or associated with the intermediary industry or the SP (internal TU). With regard to an SP, the infrastructure can be located inside the (internal TU) or outside the steel production plant (external TU) (Figure 1). Therefore, an external TU or third-party recycler can be one of the stakeholders among intermediary industry, SMS treatment company, or a third-party SP attracting SMS from other SPs.

The treated slag can be used as a raw material in EAF or by user industries. These industries can be from the existing sectors (e.g., cement and road construction) or new potential ones (e.g., glass and agriculture). Furthermore, SMS can be used as the raw material for an intermediary industry after the pre-treatment phase or in the as-received form.

The ultra-fast cooling process described in Section 3.1 is carried out inside the SP's plant, and additional processes such as grinding can be followed to prepare SMS for intermediary industries such as lime production. An example of the latter case is a new material made from SMS to be used in the glass industry to produce coloured glass.

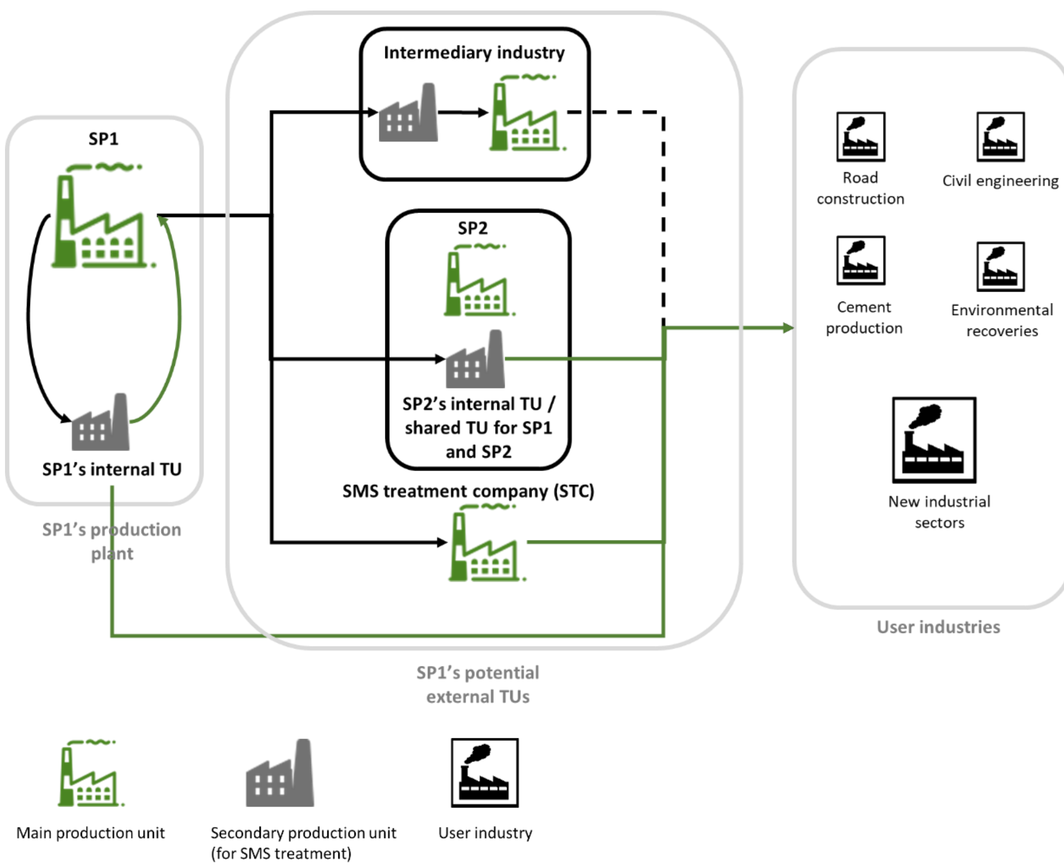


Figure 1. Potential stakeholders in the SMS value chain

Table 1. Stakeholders in the SMS value chain

Stakeholder	Description	Aim	Potential means
SP	A company specialised in steel production and, therefore, has the decision-making power on its slag.	To maximise the company's profit and align its SMS value chain with the legislation to eliminate SMS landfilling, to reduce the challenges and costs of SMS handling and transport	Internal TU for SMS treatment, selling to external Tus, and collaboration with other SPs to find shared value chains.
SMS treatment company	A company with the core activity on the slag treatment processes.	To maximise the profit from SMS treatment.	Innovative technologies, attracting a high volume of SMS, and production of highly valorised treated slag.
Intermediary industry	A company/An industrial sector that potentially can integrate slag recycling and processing within its current processes with or without the need for additional recovery actions; Its core activity is not slag treatment (e.g., lime production industry).	To increase the production efficiency by using treated SMS as a substitution for natural raw materials, and increase profit from SMS to produce new products.	Innovative technologies, collaboration with SPs to discover and share new SMS value chains, and attract a high volume of SMS.
Third-party recycler / external TU	A company/an industrial sector that buys and treats the SMS from the SP. It can be one of the stakeholders from the categories of intermediary industry, SMS treatment company, or third-party SP.		
User industry	A company/An industrial sector that uses the treated slag as raw material without additional treatments (e.g., road construction, cement production, civil engineering, environmental recoveries). The user industry acts as an intermediary industry if it carries out SMS treatment activities.	To increase the efficiency by using treated SMS as a substitution for natural raw material.	Innovative technologies for aligning SMS use in the production process, and search for efficient means to reduce the cost of raw materials by substituting SMS.
Policymakers	A regional/national legislative body responsible for regulations related to the treatment and use of SMS.	To reduce landfilling volume and align with environmental regulations; (Possibly) willing to make its region a hub for best practices in the SMS value chain.	Improved legislation for maximising the SMS value chain valorisation, incentives for new SMS value chains within industrial symbiosis and circular economy initiatives, imposing penalties for SMS landfilling, improving the know-how and technological advancement, and identification of the potential degree of collaboration within SPs.

Due to SMS challenging features described in Section 3.1, experts believe that it should be treated and marketed in the proximity of the SPs, preventing any flow to farther regions or countries. Therefore, the geographical dimension of the problem is limited to a region where the

SPs are located. The exact area for each case depends on the SPs' location and position and the homogeneity of regulations and markets.

The best practices for one SP might differ from another SP due to reasons such as steel type and slag cooling processes. Also, collaborations within a steelmaking region may result in synergies that might vary from the analysis each SP carries out independently for its slag value chain. Therefore, the value chain study needs a holistic approach, different from the perspective of a single SP. The potential stakeholders interested in such a holistic analysis can be the policymakers, SMS treatment companies, intermediary industries, and the SP/group of SPs currently recycling slag and evaluating the opportunities to expand their businesses.

For simplicity, we refer to these potential stakeholders and the regional approach as "system level". This approach is different from the approach of one SP searching to valorise its slag value chain since the best practices at the system level may not necessarily favour each SP from the latter group.

Consequently, a potential decision support system (DSS) should satisfy the following requirements to solve the problem:

R1. Formalization of the problem defined in this section to support the qualitative and quantitative evaluation of possible solutions.

R2. Definition of potential SMS value chain configurations, considering the collaborative aspects and the role of TUs in their supply chains.

4. AHP model development

Among the models in the literature, AHP was selected to support the selection of the most promising novel value chain thanks to a structured approach that helps formalise qualitative and quantitative criteria while taking advantage of expert judgments (R1). Indeed, AHP is a multi-attribute decision method (Saaty, 1990) used in making new, complex, or strategic decisions.

Following the AHP steps, we first define the set of possible solutions (R2) for the addressed problem (Section 4.1). This set targets possible scenarios in the SMS value chain regardless of each EU region's specific characteristics. Then, criteria and sub-criteria are identified (Section 4.2) and weighted (Section 4.3), considering the literature and interviews with stakeholders.

4.1. Generation of alternatives

The alternatives are distinguished according to:

- TU owners, consisting of SPs, intermediary industries, and SMS treatment companies,
- location of TUs and geographical coverage of SPs and treated SMS,
- pre-treatment activities (e.g., slow and fast cooling, magnetic separation, dry and wet granulation), and
- internal and external use of the treated slag.

Therefore, the alternatives are defined as follows:

A1. Owned TU for user industries: The treatment activities are carried out by each SP through a treatment facility in the production site. The final product is sold to user industries.

A2. Owned TU for internal use: Treatment activities by each SP are dedicated to internal use as the raw material in the steel production (i.e., in EAF production, as a substitution of lime and scrap), preventing any external flow from the steel production site.

A3. Shared TU: A cluster of SPs collaborate to treat the SMS through sharing a TU and its revenues. The final product can be either used by the SPs or sold to user industries.

A4. Shared TU with local pre-treatment units: A cluster of SPs collaborate to treat the SMS through sharing a TU, establishing pre-treatment units at each producer's site, and sharing the revenues of SMS treatment.

A5. External TU: The treatment activities are carried out by a third-party recycler from the categories of intermediary industry, SMS treatment company, and third-party SP that buys the SMS from the SPs in a region and carries out the treatment, marketing and selling activities.

A6. External TU with local pre-treatment units: The treatment activities are carried out by a third-party recycler with pre-treatment units at each producer's site.

Table 2 reports the list of alternatives and relevant actors. The TU owner is the responsible entity with which the benefits and challenges of the slag treatment are associated. System-level stakeholders are the entities interested in evaluating the six alternatives within their region. System-level analysis scale shows how the results for each alternative should be aggregated so that the alternatives can be comparable. In principle, it is based on the TUs and their owners.

Table 2. List of the alternatives

	Alternatives	**Use**	**TU owner(s)**	**System-level analysis scale**	**System-level stakeholders**
A1	Owned TU	Sell to user industries	Single SP	(Multiple) Overall analysis of all single SPs (TUs)	Potential stakeholders: e.g., policymakers, intermediary industries, SMS treatment companies, and SPs
A2	Owned TU	Internal use			
A3	Shared TU	Sell to user industries (and SPs internal use)	A cluster of SPs	(Multiple) Overall analysis of all shared TUs	
A4	Shared TU with pre-treatment units				
A5	Central TU(s)	Sell to user industries (and reuse in steel production)	Third-party recycler	(Single) Third-party recycler	
A6	Central TU(s) with pre-treatment units				

4.2. Decision hierarchy

The decision hierarchy consists of structuring the challenges by defining the criteria to evaluate the alternatives (Figure 2). Each criterion is screened to be independent of the others, not redundant, and without the same importance among the alternatives to help evaluate them. The first- and second-level criteria are briefly described in this subsection.

C1. Technology readiness

The technological status and the evaluation of its innovativeness are crucial criteria (Chen et al., 2006; Sarkkinen et al., 2019; Wang et al., 2012). To this aim, the availability of the technology (Chan et al., 2008; Chan and Kumar, 2007; Kengpol and O'Brien, 2001; Lin et al., 2010), the level of know-how and experience (Aragonés-Beltrán et al., 2014; Ozorhon et al., 2018; Samah et al., 2010; Wörsdörfer et al., 2015), required skills (Kengpol and O'Brien, 2001), the reliability of the final product and technology, and production capability (Chan et al., 2008; Ozorhon et al., 2018; Tai et al., 2011) are evaluated.

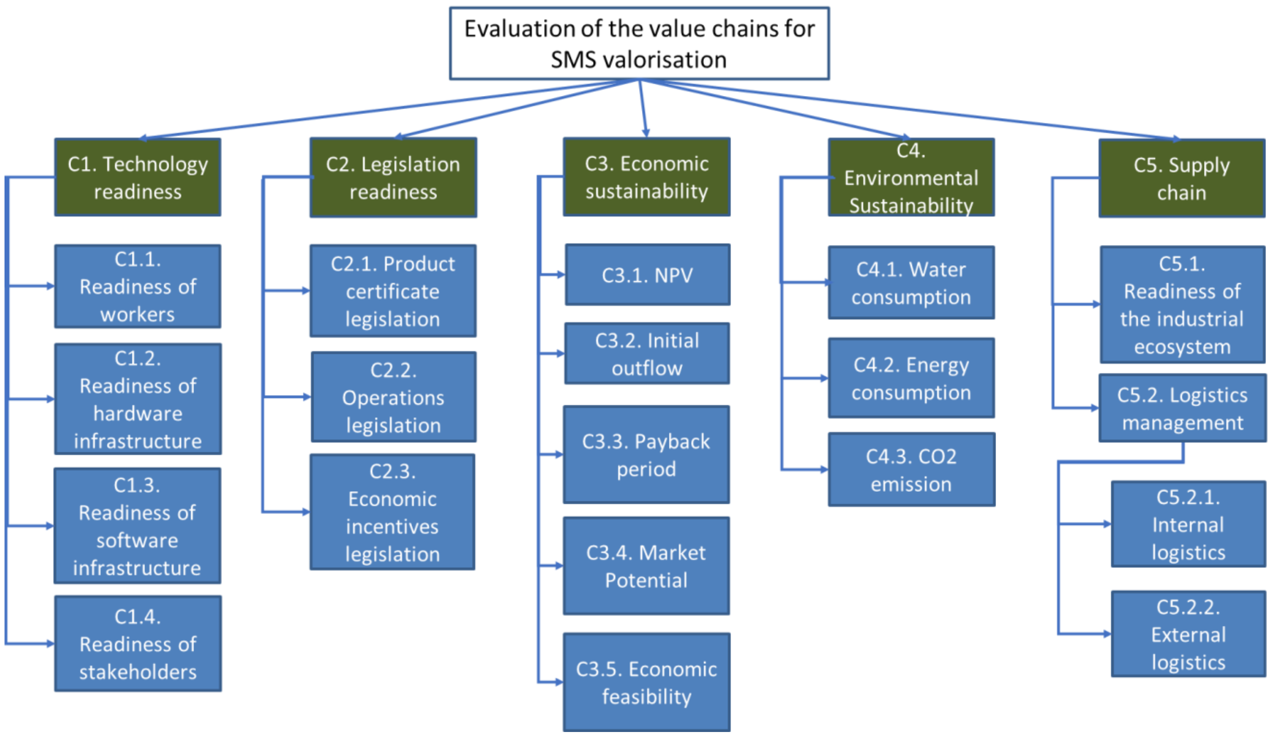


Figure 2. Decision hierarchy

Consequently, infrastructure readiness is a prerequisite for new value chains (Chan et al., 2008; Mahjouri et al., 2017). The new hardware and software infrastructure should be aligned with the existing ones (Wörsdörfer et al., 2015; Yusuff et al., 2001). Space is a limiting factor for analysing hardware infrastructure (Delmonico et al., 2018), and in an industrial symbiosis, its readiness for sharing among the partners should be assessed (K.E.K et al., 2019). The sub-criteria for technology readiness are listed in

Table 3.

Table 3. Sub-criteria description for technology readiness

Sub-criteria	Description
C1.1. Readiness of	New processes for SMS treatment require workers' skills to adapt the new technologies to the current ones, efficiently use them, control the quality and

workers	carry out the machines' maintenance.
C1.2. Readiness of hardware infrastructure	The company's capability to dedicate space for the infrastructure of new technologies, share it with partners, if necessary, and align its existing infrastructure with the new ones.
C1.3. Readiness of software infrastructure	The integration of software for treatment processes with the internal software infrastructure, potential partners, and customers facilitating decision-making in terms of production and supply chain planning.
C1.4. Readiness of stakeholders	Potential customers' technological readiness to accept a secondary raw material (treated slag) and carry out necessary post-treatment activities as a replacement of natural raw material.

C2. Legislation readiness

The role of the regulations and policies in the whole value chain, from raw material to the final product (Ozorhon et al., 2018; Wörsdörfer et al., 2015), are analysed by identifying the conformance with certifications (Chan et al., 2008; Wang et al., 2012), tariffs and taxes (Chan and Kumar, 2007; K.E.K et al., 2019), and hazardousness of the material (Lin et al., 2010; Wörsdörfer et al., 2015). The sub-criteria for legislation readiness are listed in Table 4.

Table 4. Sub-criteria description for legislation readiness

Sub-criteria	Description
C2.1. Product certificate legislation	Certificates for treated slag to evaluate its chemical and physical features according to the specific industrial segment for its application (e.g. the safety criteria proposed by Remus et al. (2013)). It is a proof that the manufacturer is authorised to place the products in the market that comply with technical standards guaranteed over time by a controlled factory production system (i.e., CE marking).
C2.2. Operations legislation	Legislation for the pre-treatment and treatment procedure and material recovery of slag as the final recycling phase. The legislation should encourage and simplify the slag application of the four criteria currently based on the by-product definition (i.e., origin from the production process, certainty of use, direct use, compliance with quality and environmental requirements) through specific and uniform local rules.
C2.3. Economic incentives legislation	Subsidies and incentives help prevent slag landfilling and promote its treatment. Special regulations can incentivize the slag application in immature industrial segments. Local regulators should facilitate slag treatment by releasing restrictive legislation that is not coherent with the relevant EU ones (e.g., REACH and waste hazardousness regulations).

C3. Economic sustainability

One principal factor is the economic and financial feasibility (Kengpol and O'Brien, 2001; Leong et al., 2017; Lin et al., 2010; Sarkkinen et al., 2019). The relevant factors include revenue (price and quantity) (Chan and Kumar, 2007; Wörsdörfer et al., 2015), operating and capital expenses (Chan et al., 2008; Gusmerotti et al., 2019; Ozorhon et al., 2018; Samah et al., 2010), and supply chain costs (Chan et al., 2008; Chan and Kumar, 2007). In addition, regarding the evaluation of new investments, investment cost (Aragonés-Beltrán et al., 2014; Tai et al., 2011), Net present value (NPV) (Chen et al., 2006), funds availability (Ozorhon et al., 2018), and financial indicators (Metaxas et al., 2016; Ozorhon et al., 2018) are fundamental issues.

Identifying the right market is another critical criterion that supports economically sustainable solutions (Metaxas et al., 2016), where customers' responsibility and demand should be evaluated (Chan et al., 2008; Chan and Kumar, 2007; Tai et al., 2011). Also, applications in a potential market (especially for by-products) (Kaźmierczak et al., 2019) and the outlook for its growth (Wang et al., 2012) are other crucial aspects. Regarding the evaluation of new investments, it is critical to analyse the competition in the market (Aragonés-Beltrán et al., 2014; Chen et al., 2006; Tai et al., 2011), diversification of potential customers (Aragonés-Beltrán et al., 2014; Salgado et al., 2012), and the maturity of the market (Chen et al., 2006; Ozorhon et al., 2018; Wörsdörfer et al., 2015). The sub-criteria for economic sustainability are listed in Table 5.

Table 5. Sub-criteria description for economic sustainability

Sub-criteria	Description
C3.1. NPV	New investments should have a positive NPV to prove their profitability. High overall values of NPV at the system level prove the profitability of the TU owners.
C3.2. Initial outflow	A low overall value on initial outflow represents good affordability among the TU owners at the system level. This sub-criterion is an entry requirement for an external investor and is particularly challenging for small SPs with low production rates.
C3.3. Payback period	Depends on the financial capabilities of an investor. For the investors who invest in slag treatment as a core business, a short-term period is desirable. An average acceptable value of the payback period proves the return on investment at the system level.
C3.4. Market potential	Considers product variety and volume by evaluating the proportion of the valorised volume of the slag. It also considers the accessibility to the market, which is due to the variety of steel and slag types. A high level of know-how and experience can bring more innovative product mix features. The granularity of slag can also lead to a broader product mix.
C3.5. Economic feasibility	An optimum slag value chain at the system level should consider the proportion of TU owners that profit from that value chain. Calculating the overall values and averages in an aggregated way in C3.1, C3.2, and C3.3 risks omitting the negative values for some TU owners. This sub-criterion helps identify these TU owners not benefiting from one of these sub-criteria.

C4. Environmental sustainability

Environmental impact drives companies to a positive image of social responsibility (Abba et al., 2013; Kang et al., 2018). Quantifying emissions (e.g. greenhouse gas) is a prominent environmental factor (Gusmerotti et al., 2019; Turcksin et al., 2011). Other factors are water pollution and consumption (Samah et al., 2010) and conservation of natural resources (K.E.K et al., 2019; Ozorhon et al., 2018). Environmental impacts of landfilling, such as space, are other criteria for waste management (Gusmerotti et al., 2019). The sub-criteria for environmental sustainability are listed in Table 6.

Table 6. Sub-criteria description for environmental sustainability

Sub-criteria	Description
C4.1. Water consumption	Typical practices for slag cooling are based on weathering and water quenching. Watering also acts as a controlling factor to avoid scattering dust (included in SMS) in the air, avoiding pollution. The new pre-treatment technologies (e.g., ultra-fast cooling) save water consumption by preventing powder formation.
C4.2. Energy consumption	The application of slag as a raw material in user industries causes the saving in natural resources, avoiding energy consumption for the provision of natural raw materials.
C4.3. CO_2 emission	The application of slag as a raw material in user industries causes the saving in natural resources, avoiding CO_2 emissions for the provision of natural raw materials. Furthermore, the localisation of the slag supply network causes less transportation and CO_2 emissions.

C5. Supply chain

Since the cost of transportation is not negligible, it is the most prominent criterion in external logistics in the supply chain and logistics performance (Tai et al. 2011; Metaxas, Koulouriotis, and Spartalis 2016) (Linnemann et al., 2015), with a deep impact on the mobility (K.E.K et al., 2019; Turcksin et al., 2011; Wang et al., 2009, 2012; Wörsdörfer et al., 2015). Consequently, for the problems dealing with the location aspects of the facilities, the proximity between the source and destination is a vital factor (Asefi et al., 2020; Chan et al., 2008; Chan and Kumar, 2007; Wang et al., 2012; Wörsdörfer et al., 2015).

Based on the raw material and final product characteristics, internal logistics (e.g. storage and material handling) is an essential criterion (K.E.K et al., 2019; Wang et al., 2012; Wörsdörfer et al., 2015). As for the ecosystem, some aspects are influential based on the complexity of the network and the involved stakeholders, such as network reliability (Leong et al., 2017), inter-firm physical exchange and organisational collaboration (K.E.K et al., 2019), community involvement (Samah et al., 2010), cooperation with authorities (Delmonico et al., 2018), consumers' cooperativeness (Lin et al., 2010), commitment of the sponsors (Yusuff et al., 2001), and partners satisfaction (Metaxas et al., 2016). The sub-criteria for the supply chain are described in Table 7.

Table 7. Sub-criteria description for supply chain

Sub-criteria	Description
C5.1. Readiness of industrial ecosystem	Concerns the collaboration opportunities through the industrial symbiosis for the stakeholders, such as SPs, potential customers, intermediary industries, associations, and technology providers. Such collaborations attract external investors and sponsors throughout the region and empower the SPs with higher bargaining power against the local authorities for updating the regulations.
C5.2. Logistics management	Consider the transportation constraints and possible TUs' locations. Challenges in SMS handling limit its transportation in the as-received form and without pre-treatment to far distances (i.e., more than 30-40 km).

4.3. Importance of criteria

The importance of the criteria was assessed by multiple experts through a survey (Figure 3). Four experts from European steel production companies with over 20 years of experience participated in the survey. Their expertise regarding each first-level criterion according to their answers to the survey is depicted in Figure 4.

The experts' judgments were expressed in pairwise comparisons between criteria, using the 9-point scale of relative importance (Saaty, 2008). The responses are inserted in the “Super Decisions” software for the analysis of pairwise comparisons ("SuperDecisions software").

The comparisons for the first-level criteria are carried out based on the knowledge gained from the interviews. Each judgement matrix of the experts had a consistency ratio of less than 0.10, thus, the resulting criteria weights can be synthesised by calculating their geometric average, considering the expertise of each respondent in each first-level criterion (Figure 4).

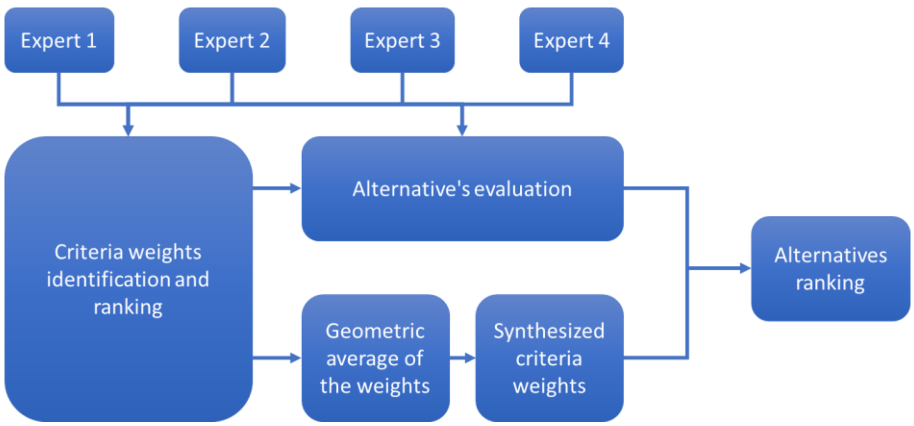


Figure 3. AHP design and results’ synthesis

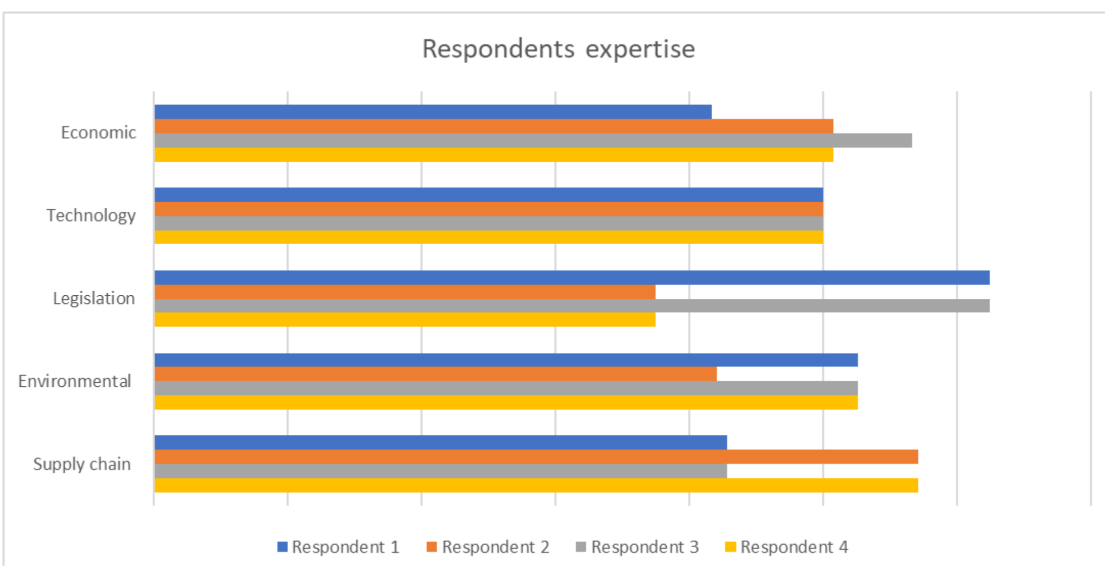


Figure 4. Respondents’ expertise in each criterion

The preference of the geometric mean over the arithmetic mean is to maintain the reciprocity property in addition to the unanimity and homogeneity ones (Aczel and Saaty, 1983). To calculate the geometric average, we consider the expertise of each respondent (q_i) deriving from the survey, represented in Figure 4. The weight of each sub-criterion is calculated by multiplication of the weights given by expert i (X_i) to the power of the expert's importance. ($\prod_i X_i^{q_i}$).

Among the first-level criteria (Table 8), economic sustainability is by far the most important one. Technology readiness, legislation readiness, and environmental sustainability have almost the same importance, while the supply chain criterion has the lowest importance. Therefore, a winning SMS value chain highly depends on economically sustainable solutions.

Table 8. Local weights

Criteria	Weight	First-level criteria	Weight	Second-level criteria	Weight
C1. Technology	0.15	C1.1. Workers read.	0.22		
		C1.2. Hardware read.	0.30		
		C1.3. Software read.	0.35		
		C1.4. Stakeholders read.	0.13		
C2. Legislation	0.17	C2.1. Product certificate leg.	0.31		
		C2.2. Operations leg.	0.34		
		C2.3. Economic incentives leg.	0.35		
C3. Economic	0.41	C3.1. NPV	0.21		
		C3.2. Initial outflow	0.21		
		C3.3. Payback period	0.13		
		C3.4. Market	0.23		
		C3.5. Economic feasibility	0.23		
C4. Environmental	0.19	C4.1. Water	0.34		
		C4.2. Energy	0.17		
		C4.3. CO_2	0.49		
C5. Supply chain	0.09	C5.1. Ecosystem read.	0.20		
		C5.2. Logistics	0.80	C5.2.1. Internal logistics	0.45
				C5.2.2. External logistics	0.55

Global weights of the leaf criteria are calculated considering the local weights for each parent criterion. They can be interpreted as the importance of each leaf criteria with regard to an ideal SMS value chain. As can be observed in Figure 5, the WS value chain strongly depends on market potential, economic feasibility, and CO2 emission. Initial outflow, NPV, water consumption, and economic incentive legislation are the other criteria of high importance. On the contrary, stakeholders' readiness and the readiness of the industrial ecosystem have the lowest rank.

The criticality of the criteria and sub-criteria show that the companies should focus more on infrastructure capabilities for establishing, maintaining, and integrating their internal technological system. Also, a potential recycler faces more challenges for the internal activities of handling and transportation rather than the external challenges with potential stakeholders. The first requirement for an economically sustainable solution is the potential market availability, which should be feasible and profitable for most stakeholders.

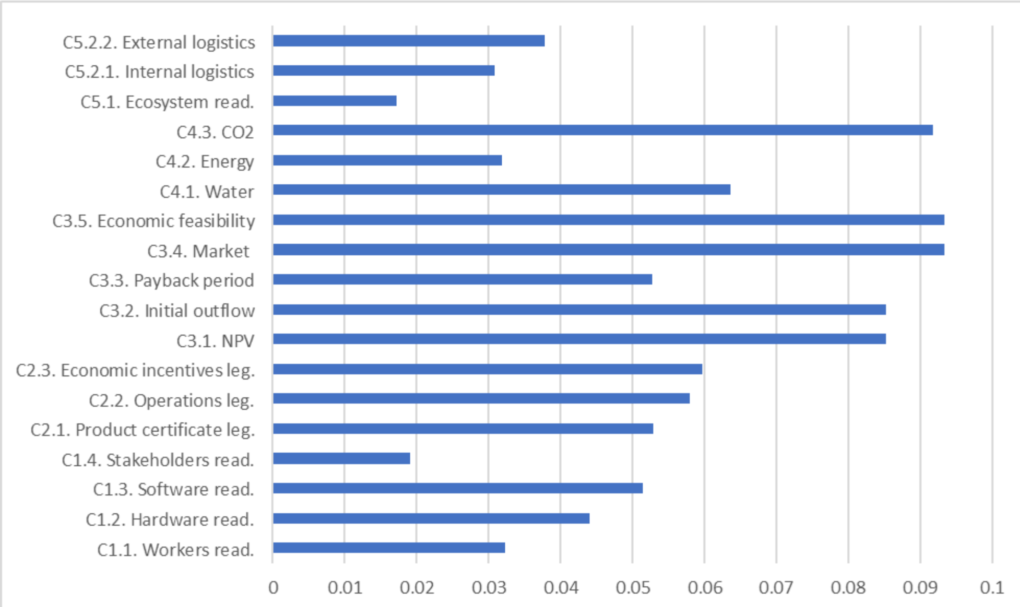


Figure 5. Global weights

5. Model application

For evaluating the alternatives, we used the data collected for the Lombardy region through databases and interviews with stakeholders in this region. Lombardy's steel production accounts for almost 56% of the Italian production volume, with an SMS generation of around 454,000 tons. However, nearly 90% of the generated volume is landfilled (Falsafi and Fornasiero, 2022).

After an introduction of the structure used for the alternatives ranking and description of their rankings against economic and environmental sustainability criteria (Section 5.1), we elaborate on their ranking (Section 5.2) and show their robustness against the changes of criteria importance (Section 5.3).

5.1. Evaluation of the alternatives

The evaluation of the alternatives is carried out by assessing the performance of each alternative against leaf criteria. Since the AHP model has both qualitative and quantitative criteria, we use different approaches to assess the performance. For the quantitative criteria (i.e., NPV, initial outflow, payback period, water consumption, and CO_2 emission), the evaluation is based on the estimation of data collected from interviews and public databases.

For the qualitative criteria, the evaluation of the alternatives is based on consultation with the experts. During interviews and discussions with them, it was possible to define the alternatives and assess their performance. The evaluation is based on absolute measurement, in that the intensity levels are calculated by asking the experts to assign a number between 0 to 1 for each level; 0 is the level with the lowest degree for a successful SMS value chain, and 1 is a facilitator.

The intensity levels for the qualitative sub-criteria are depicted in Figure 6. Furthermore, when evaluating each sub-criterion against the alternatives, the best intensity level in Figure 6 may fit no alternatives. Thus, for each sub-criterion, the values are idealised according to the maximum intensity level associated with the 6 alternatives (Table 9). The idealisation facilitates understanding the degree of variations and assures that intensities belonging to large families do not receive small priorities simply because there are many of them (Saaty, 2006).

The estimations of economic sustainability criterion are carried out for SPs in Lombardy, choosing large, medium, and small-size companies to cover all types. Initial outflow is calculated based on the following formula:

$$Initial\ outflow = (initial\ outflow\ for\ establishing\ TU(s)) + (initial\ outflow\ for\ establishing\ pre-treatment\ unit(s))$$

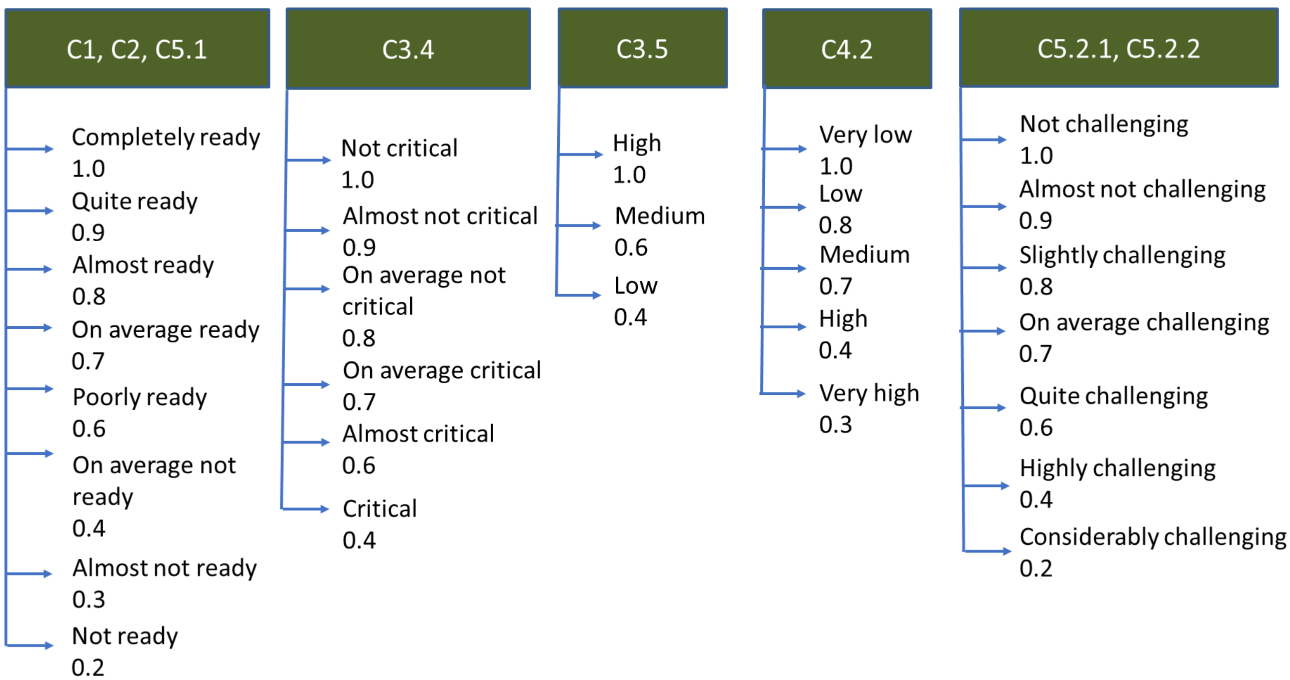


Figure 6. Definition of the intensity levels for the qualitative criteria

Table 9. Idealised values for alternatives' evaluation

Criteria	**Alternatives**					
	A1 (Owned TU / to sell)	A2 (Owned TU / internal)	A3 (Shared TU)	A4 (Shared TU + pre-treatment)	A5 (Central TU)	A6 (Central TU + pre-treatment)
C1.1. Workers read.	0.778	0.778	0.778	0.444	1.000	0.667
C1.2. Hardware read.	0.778	1.000	1.000	1.000	0.444	0.444
C1.3. Software read.	1.000	1.000	0.500	0.500	1.000	1.000
C1.4. Stakeholders read.	1.000	0.875	1.000	0.375	0.750	0.375
C2.1. Product certificate leg.	0.800	1.000	0.800	0.900	0.600	0.700

C2.2. Operations leg.	0.889	1.000	0.889	0.667	0.667	0.444
C2.3. Economic incentive leg.	0.222	0.333	1.000	0.444	0.778	0.667
C3.1. NPV	0.407	0.214	0.276	0.568	0.355	1.000
C3.2. Initial outflow	0.623	0.623	1.000	0.559	0.917	0.532
C3.3. Payback period	0.320	0.258	0.276	0.429	0.686	1.000
C3.4. Market	0.444	0.778	0.667	0.778	0.889	1.000
C3.5. Economic feasibility	0.600	0.400	0.600	0.600	1.000	1.000
C4.1. Water	0.197	0.197	0.197	1.000	0.197	1.000
C4.2. Energy	0.300	0.300	0.800	0.400	1.000	0.700
C4.3. CO_2	0.613	0.956	0.361	0.548	0.523	1.000
C5.1. Ecosystem read.	0.889	1.000	0.667	0.444	0.333	0.222
C5.2.1. Internal logistics	0.700	0.800	0.700	1.000	0.900	1.000
C5.2.2. External logistics	0.900	1.000	0.600	0.800	0.400	0.700

The second addend is considered in A4 and A6, where TU owners establish pre-treatment units.

Financial flow in the first year is calculated based on the following formula:

$$Financial\ flow\ in\ the\ first\ year = Revenue - operative\ costs$$
$$= Revenue - (treatment\ cost + transport\ cost + logistics\ cost)$$

Transport cost is calculated based on the slag production volume from the SPs to the TU, while logistics costs are calculated based on the proportion of the valorised volume of the slag. Revenue is calculated based on the price, other earnings (e.g., in A5, it is the cost of SMS as the waste transaction that the SP pays to the TU owner), and the proportion of volume valorised in each alternative as follows:

$$Revenue = slag\ production\ volume$$
$$\times [(Price + other\ earnings) \times proportion\ of\ the\ valorised\ volume\ ]$$

Financial flow for the following years is calculated based on the yearly growth rate in each alternative. The discounted payback period is calculated considering the number of years after which the NPV becomes a positive value.

The results for the economic sustainability criterion are aggregated and represented in Table 10. The calculation methodology is based on the system-level analysis scale shown in Table 2. In other words, the initial outflow and NPV for each alternative is the summation of the relevant values for each SP for A1 and A2, each cluster of SPs for A3 and A4, and third-party recycler for A5 and A6. The discounted payback period is the average of the corresponding values.

Regarding the market potential sub-criterion, the higher the number of customer sectors and product mixes, the better the market to attract the treated SMS. In A2, since the supplier and customer of the treated SMS are the same, the market is already stable. In A6, due to the product mix, the customers are diverse, and therefore, there is high market potential.

Furthermore, A6 has the highest competitive advantage due to the high specialisation in the treatment and pre-treatment processes. Consequently, the third-party recycler in this alternative can use this advantage to develop new products for new applications. Since the customer and supplier in A2 are the same SP, its competitive advantage is high. In the other alternatives, there is an average level of specialisation, and therefore, the recyclers have an average competitive advantage.

The broad geographical coverage of the treated slag and, therefore, access to a relatively extensive potential market causes A3 to A6 to have high market demand. The higher volumes of treated slag in these alternatives, compared to A1 and A2, also result in large market coverage.

Table 10. Aggregated results for the alternatives in the economic sustainability criterion

Criteria		**Alternatives**					
		A1 (Owned TU / to sell)	A2 (Owned TU / internal)	A3 (Shared TU)	A4 (Shared TU + pre-treatment)	A5 (Central TU)	A6 (Central TU + pre-treatment)
C3.1. NPV (€)	Value	58,582,990	30,782,443	39,804,368	81,847,380	51,092,785	144,102,189
C3.2. Initial outflow (€)	Value	26,500,000	26,500,000	16,500,000	29,500,000	18,000,000	31,000,000
C3.3. Payback period (year)	Value	7.5	9.3	8.7	5.6	3.5	2.4
C3.4. Market	Intensity level	Critical	On average critical	Almost critical	On average critical	On average not critical	Almost not critical
C3.5. Economic feasibility	Intensity level	Medium	Low	Medium	Medium	High	High

Two activities mainly differentiate the CO_2 emission in the 6 alternatives, namely transportation and slag cooling. Water cooling methods are the alternatives' main differentiating factors of water consumption. The advantage of the pre-treatment process based on dry granulation, compared to the traditional cooling process based on wet granulation, is the lower CO_2 emission and water consumption. According to the interviewed experts, dry granulation is expected to save almost 30 kg CO_2/ton of slag, more than wet granulation.

Regarding the cooling methods, the difference between the traditional (A1, A2, A3, and A5) and innovative cooling (A4 and A6) is, on average, 15 kg/ton. The treatments in A1, A2, A3, and A5 consume, on average, 15 m^3/ton more water than in A4 and A6. Energy consumption in A5 is the lowest since the SMS treatment is carried out in one central TU. Energy consumption of the other alternatives is based on the number of treatment plants and the presence of the pre-treatment unit.

5.2. Alternatives' ranking

The local desirability value (*Ldv*) is the result of evaluating the alternatives against each leaf criterion in terms of values between 0 and 1 (Figure 7).

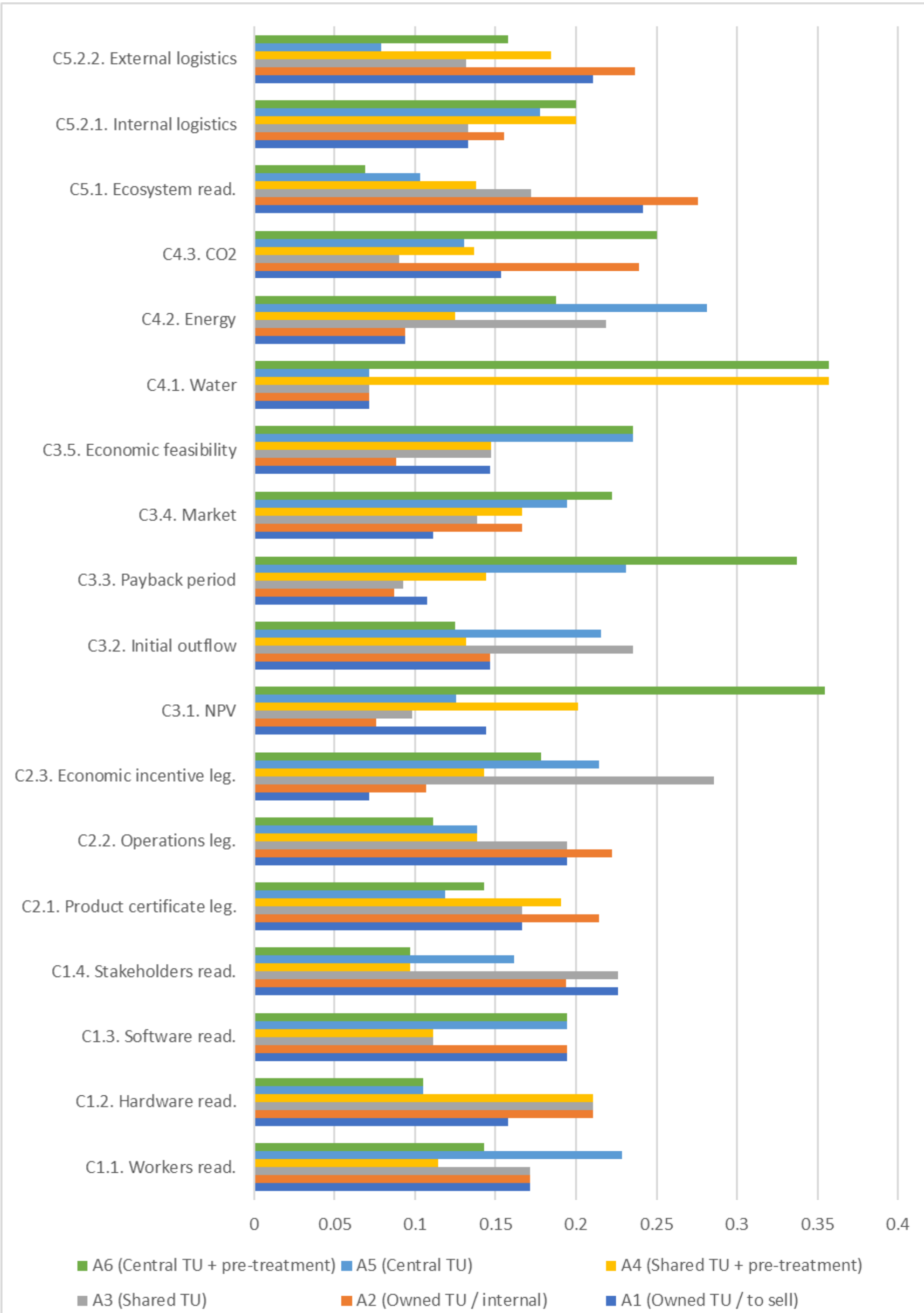


Figure 7. Local desirability values

Considering the *Ldv* for each leaf criterion *i* and the global weights (*gw*) of the criteria, the global desirability value (*Gdv*) for each alternative *j* is calculated as follows and shows each alternative's ranking among others:

$$Gdv^j = \sum_i (gw_i . Ldv_i^j)$$

Consequently, according to *Ldv* and *Gdv* (Figure 8), A6 has the highest priority, followed by A5, A4, A2, A3, and A1. The pairs A2-A3 and A4-A5 have almost the same priority. A6 is predominant in environmental and economic sustainability criteria (Figure 9). Within these criteria, the highest rank of A6 is associated with the predominance of NPV, payback period, market potential, economic feasibility, water consumption, and CO_2 emission. However, the readiness of technology and legislation are the most challenging criteria that may prevent A6 from fully exploiting its advantages.

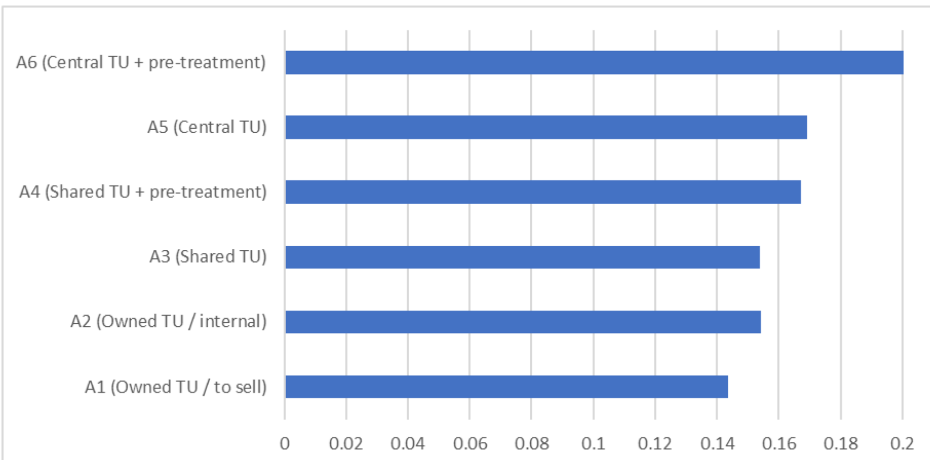


Figure 8. Ranking of alternatives based on Gdv

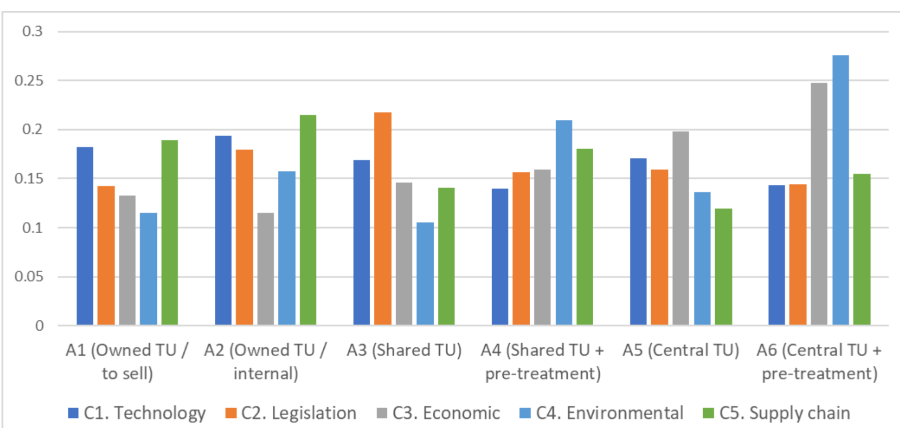


Figure 9. Ranking of first-level criteria for each alternative calculated based on Ldv

Considering the evaluation of the first-level criteria against alternatives (Figure 9), the technological readiness of A4 and A6 is not ready as much as the others. From the legislative point of view, A3 ranks first, thanks to the priority of economic incentives. From the supply chain point of view, A2 and A1 have preferences compared to the others. The advantage of A2 is mainly related to the internal use of slag, which prevents external handling and transportation activities.

5.3. Sensitivity analysis

The robustness of the AHP ranking can be tested against possible arbitrary responses by conducting a sensitivity analysis on the first-level criteria (Figure 10). Sensitivity analysis shows the changes in priority and ranking of the alternatives when the weight of each criterion changes. The dashed lines in Figure 10 represent the optimal priority of each alternative.

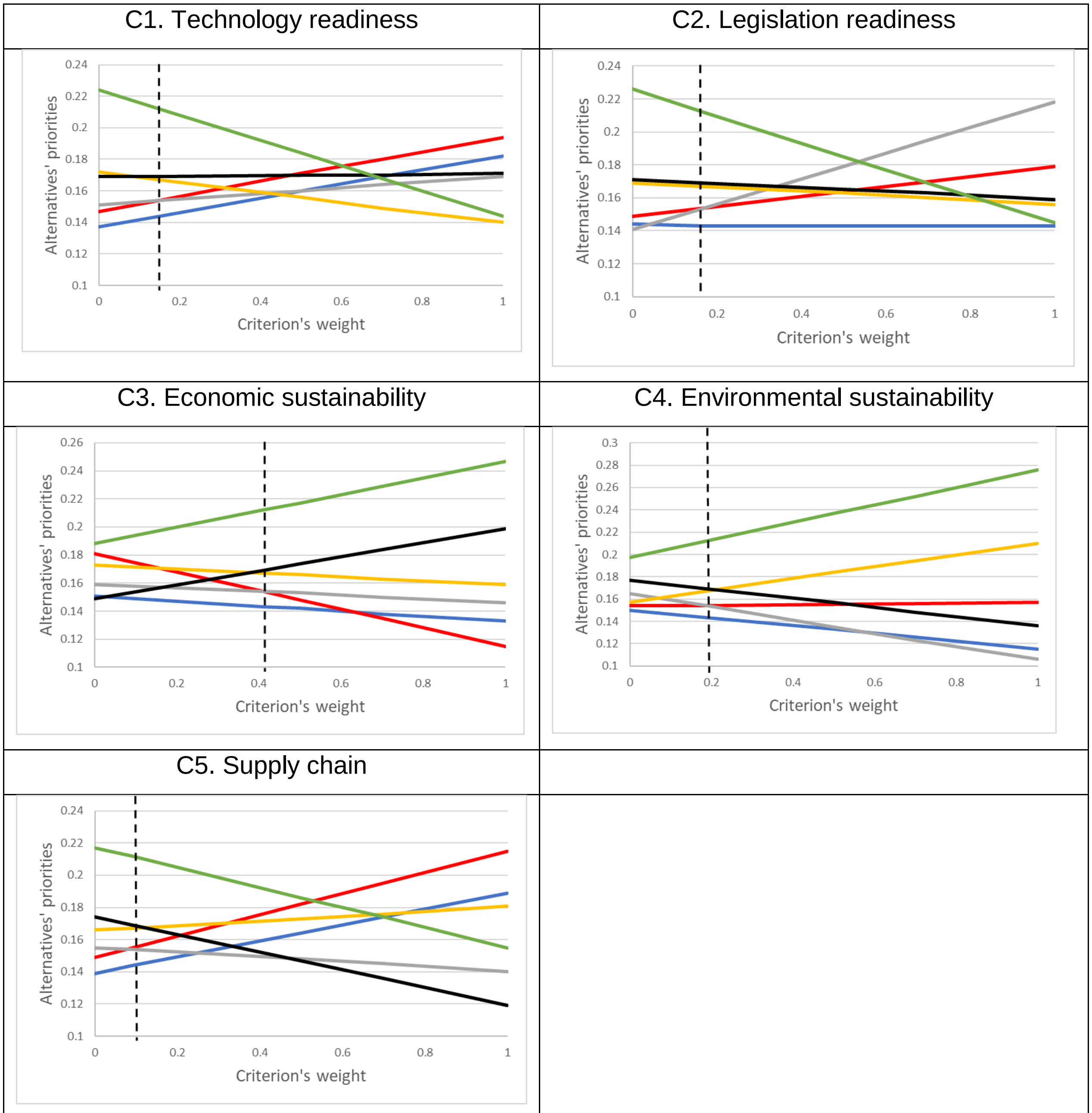
The ranking of A6 is robust against the changes in all criteria within a reasonable range (up to almost 30% changes compared to the initial rank). However, the pairs of A2-A3 and A4-A5 are highly sensitive to the changes in nearly all criteria (except legislation readiness for A2-A3). Considering the fact that the priority of these pairs is almost equal, the changes result in the predominancy of one over the other.

By increasing the weight of technology and economic sustainability, A5 takes over A4, while for weight increase of environmental sustainability and supply chain, A4 takes over A5. Regarding the A2-A3 pair, increasing the weight of legislation and economic sustainability causes the predominance of A3 over A2. On the contrary, increasing the weight of technology readiness, environmental sustainability, and supply chain causes the predominancy of A2 over A3. A1's priority is robust against the changes of the legislation criteria, while its robustness within around 20% to 30% changes compared to the initial ranking.

6. Discussion

The AHP model is based on a systemic approach and considers the whole value chain for a potential slag recycler. According to the experts involved in this study, alternatives' ranking shows that the pre-treatment phase has an essential role in the slag value chain since it facilitates the logistics management of SMS and has crucial environmental advantages (A4 and A6). The financial and economic estimations show that alternatives with pre-treatment are economically more attractive for recyclers, with a reasonable NPV and payback period on the investment for pre-treatment infrastructure. However, legislation and technological aspects are the most challenging issues.

Attracting the slag from other SPs to treat a larger volume is a better choice (from A3 to A6) with respect to the case where the SPs recycle the slag independently (A1 and A2). Nevertheless, the internal use carried out independently by each SP has benefits in terms of supply chain and legislation aspects. In the case of treating an aggregated amount of SMS from more than one SP (from A3 to A6), the alternatives involving the collaboration with a third-party recycler (A5 and A6) are preferred to a consortium of producers collaborating for slag recycling (A3 and A4), mainly due to the broader market coverage, environmental sustainability, and higher profits for the recycler.



Alternatives	Optimal rank	
A1	6	
A2	4	
A3	5	
A4	3	
A5	2	
A6	1	

Figure 10. Sensitivity analysis on the first-level criteria

In the AHP model, the definition of the criteria and alternatives are defined as a general framework. The alternatives are evaluated for a specific case of Lombardy to validate the results. In particular, considering the explorative approach, we analysed the role of stakeholders, pre-treatment and treatment facilities, and their locations in the model. Within this approach, we added the collaborative aspect in the SMS ecosystem by differentiating treatment activities into pre-treatment and treatment in the model.

In addition to similar studies analysing the role of industrial stakeholders (e.g., SPs), this paper also considers the role of policymakers as one of the crucial actors benefiting from the slag value chain. Through a system-level approach, we defined and evaluated the alternatives so that the benefits and challenges could be associated with all relevant stakeholders. The policymaker in this context can reinforce this motivation by offering additional benefits, such as financial and technological support. Through these supports, the SPs become more resilient to tackle future obstacles. Also, the development and penetration of innovative treatment technologies through the industrial ecosystem cannot be applied without the support of policymakers. These activities make SMS an effective and efficient substitute for natural raw materials in the market.

The Lombardy region, as a European hub for scrap-based steel production, is a suitable benchmark for industrial symbiosis and circular economy opportunities, representing successful synergic scenarios from slag exchange. This study can be helpful for SPs to decide on the feasibility and profitability of establishing independent TUs, collaborating with other SPs in the region, or selling SMS to recyclers. It can also be helpful for potential organisations, such as governmental bodies willing to analyse the regional perspective and potential industrial sectors interested in slag recycling and new business models, such as lime producers (Rieger et al., 2021).

7. Conclusions

In this paper, we propose a framework to consider the role of innovative technologies in developing new value chains in industrial symbiosis for SMS. These technologies can support an efficient pre-treatment of SMS thus reducing the environmental impact. The study investigates different decisional options, namely standalone and collaborative value chains. Compared to the literature, where the focus is mainly on a limited number of criteria (such as environment, economy, and technology), this study creates a holistic framework where a set of heterogenous criteria are considered. For this reason, a multi-criteria combined with a multi-expert approach within the AHP helps balance the importance of different criteria from the actors' points of view, such as steel producers and technology providers.

The developed model is applicable to similar value chains. Since the alternatives and the criteria in the AHP focus on typical value chain characteristics in Europe, the model proposes a pattern which can be helpful for the stakeholders in other European regions. Furthermore, given the current economic instability, a critical dimension is the increasing inflation rate. Thus, any possible solution can include a sensitivity analysis by considering this aspect. Another factor influencing the results is the evolving trend of some criteria. For instance, the heterogeneous regulations across Europe ask for harmonisation in the near future. Furthermore, technology availabilities in each region are strongly influenced by rapid technological advancements, and therefore, any replication of the results should consider these trends.

The AHP model results demonstrate one alternative's effectiveness over the others. As further research, it would be useful to develop a model for each ecosystem by considering its characteristics and applying different alternatives for different SPs based on their dimensions and geographical proximity. To this aim, optimisation and discrete-event simulation techniques can be utilised to further model different scenarios and find the best configuration. Another potential evolution would be to explicitly consider uncertainty of the judges within the AHP method in order to increase the robustness of the results (Manassero et al. (2004)).

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