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Early-stage assessment of minor metal recyclability

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ABSTRACT

The growing demand for minor metals creates both pressure on the supply chain of these metals and challenges in waste management. Consequently, there is a wide interest in recycling opportunities. To identify these opportunities, it is key to understand bottlenecks and drivers in recycling value chains. Hence, we analyzed existing recyclability frameworks and related recycling literature, revealing 113 factors that determine the success of recycling minor metals. These factors were linked to the stages of the recycling value chain, i.e. manufacturing, use phase, waste collection, preprocessing, metallurgical recovery and secondary marketing. Based on the insights from the literature analysis, we propose a novel recyclability assessment framework. The framework indicates how properties of products, recycling technologies and society determine recyclability. The framework is suitable for assessing the recyclability of minor metals during the recycling technology development process. Therefore, it includes indicators that can be quantified easily, as demonstrated in three case studies. As such, it can be a useful tool to guide policy makers and technology developers towards closing material loops.

1. Introduction

1.1. Supply challenges of minor metals

Modern societies are expecting serious challenges in meeting future demand for minor metals, a group of metals that includes rare earth elements, precious metals, and specialty metals. The minor metals have in common a small market size compared to that of base metals, and they are often critical for modern technologies. This dependence is increasing, among others due to the rapid adoption of energy-efficient appliances and renewable energy technologies (Tercero Espinoza et al., 2019). Therefore, minor metals are often regarded as critical raw materials. In contrast with this demand-side growth, the production chain has limited possibilities for upscaling, because many minor metals are mined as by-products of base metals (Nassar et al., 2015). Moreover, the elevated environmental burdens associated with mining and refining many minor metals can provoke resistance to upscaling from local communities and governments (Conde, 2017) while inadequate waste treatment raises equally large concerns (UN, 2019).

It is widely recognized that for a sustainable supply of minor metals, recycling is essential (Reck and Graedel, 2012; Rombach and Friedrich, 2014). Recycling increases the availability of raw materials and the environmental impacts are often lower than those of mining (Mathieux et al., 2018). Nevertheless, most minor metals currently have very low recycling rates (Graedel et al., 2011; Mathieux et al., 2018). To close the gap between actual and potential recycling, a range of policy measures is available, targeting various stages of the recycling chain. These stages include manufacturing, collection, preprocessing, recovery and the secondary market. What policy interventions are effective is material-specific (Hagelüken et al., 2016) and requires knowledge of each element in the value chain. Studies of success factors and barriers for recycling are discussed in the next section.

1.2. Assessing recyclability

Recyclability has been investigated in various contexts. For metals in general, materials and WEEE, recyclability assessment methods have been proposed (Johnson et al., 2007; Mueller et al., 2017; Oguchi et al., 2011; Phillis et al., 2005; Sun et al., 2016; Villalba et al., 2002; Winterstetter et al., 2016; Zeng and Li, 2016). These methods typically address one or more aspects that enable or inhibit recycling, using quantitative or qualitative indicators. We are unaware of methods focusing on minor metals. Yet, the body of related literature shows that different approaches are possible and indicates methodological challenges. The differences in recyclability assessment methods appear to stem from different perspectives held by each actor in the value chain.

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Below, the perspectives that occur in the literature are discussed.

Before reviewing these studies, it is instructive to first define recyclability. As one of the first, Henstock (1988) introduced the concept of recyclability, which he defined as the technical ease and economic feasibility of recovering materials from products that would otherwise enter the waste stream. In contrast, Huisman et al. (2003) defined the concept from an environmental point of view, describing the extent to which a product's recycling can reduce environmental impacts. Zeng and Li (2016) give a thermodynamics-oriented definition based on statistical entropy. From a designer perspective, recyclability indicates whether product design facilitates recycling (Chen et al., 1994). In this paper, we adopts the definition proposed by Henstock, while explicitly considering all stages in the recycling value chain.

A macro-level insight into recyclability can be obtained using thermodynamic (Anctil and Fthenakis, 2013; Johnson et al., 2007; Zeng and Li, 2016) or economic (Villalba et al., 2002) indicators. These approaches are based on the principle that lower metal concentrations require more purification efforts (Reuter et al., 2013). This is a product-centric view (Reuter et al., 2013), which does not consider organizational aspects or the characteristics of recycling technologies.

Arguing from a waste collection perspective, Oguchi et al. (2011) categorized waste flows based on the number of products and product size. This aligns with the view of waste collection companies, who consider the product properties as a given. In contrast, products can be optimized for recycling from the designer's point of view. Product properties that hinder the preprocessing or recovery process can be formulated as design guidelines. This approach was taken by Hultgren (2012) and resulted in a set of design for recyclability (DfR) guidelines. A manufacturer can apply these guidelines as part of a circular business model, in which successful recycling yields financial benefits.

Other researchers based their approach on the similarity between geologic and technospheric resource mining (Mueller et al., 2017; Winterstetter et al., 2016). Both frameworks are intended as a tool in pre-feasibility or feasibility studies. This analogy was most thoroughly elaborated by Winterstetter et al. (2016), who adapted the UNFC-2009 framework to evaluate and classify secondary resources. The perspective adopted by Winterstetter et al. (2016) is that of a recycling company, seeking exploitable secondary resources. From this perspective, legislation and collection systems are seen as external factors. Here, the core factors relate to business economics, and support in-between go/no-go decisions. Both frameworks (Mueller et al., 2017; Winterstetter et al., 2016) comprise an elaborate set of aspects, while identifying limited data availability as a challenge for quantitative comparisons.

A gap in literature, addressed in this study, becomes apparent from the difference between technical and social studies. Papers with a technical perspective address aspects of preprocessing and recovery processes (e.g. Sun et al., 2016). This view emphasizes metallurgical and material-related aspects. Two technical approaches can be distinguished: material-centric and product-centric (Reuter et al., 2013). The material-centric approach focusses on the recycling rates of single materials, whereas the product-centric approach optimizes the recycling of all materials found in a product. In contrast, papers with a sociological approach argue that recyclability also depends on the societal setting (Gusmeroli, 2017; Lapko et al., 2019). Social aspects include behavior, networks and expectations of actors throughout the recycling value chain. Both the technology-centered view and the organizational perspective describe certain aspects of the recycling system. Sometimes, a holistic view is desired (Lapko et al., 2019), covering both technical and organizational aspects over the whole value chain.

1.3. Towards a novel framework for minor metals

Against the background of diverging perspectives on recyclability, the objective of this study is to provide a structured overview of the field. This overview highlights the applicability of previous findings to minor metals. Based on these insights, a novel framework is presented to conceptualize and assess the recyclability of minor metals. The framework aims to answer the question which economic, technical, and societal factors affect the recycling of minor metals. These insights are relevant to industrial actors throughout the product life cycle. Moreover, the framework supports policy makers to identify bottlenecks in the recycling chain as targets for circular economy policies.

As part of the proposed framework, this study provides a set of indicators for recyclability. Since the recycling industry for most minor metals is nonexistent or underdeveloped, the framework focuses on providing guidance in the pre-feasibility phase. At that stage, many alternatives are typically available while detailed information is limited. Therefore, simple indicators were preferred over rigorous evaluation methods. The framework addresses recyclability in the scope of developed countries.

2. Methods

The approach of this study builds on the insights from previous research to obtain a complete and consistent framework. This recyclability assessment framework was developed in three steps, i.e. the collection of relevant literature, the identification of aspects of recyclability, and the construction of a novel framework.

The first step aims to create an overview of recyclability research. In this step, available literature was collected using Google Scholar and the following initial search queries:

- `(Recyclability OR ”recycling potential”) AND (”minor metal” OR ”critical metal”)`
- `(”Urban mining” OR ”secondary resource”) AND (classification OR indicators) AND framework`
- `Recycling AND (challenges OR issues OR barriers OR ”success factors”)`
- `(”design for recycling” OR ”design for recyclability”) AND metal*`

The identified articles were screened on their relevance based on the title and abstract. We excluded articles that did not study recycling of metals or did not focus on challenges and success factors. After screening, 15 articles remained. This initial list was extended through the snowballing technique, i.e. by checking the references of articles yielded by the initial search. The resulting list comprised 25 articles on which the systematic literature analysis was based.

Using the iterative literature collection approach, we identified both articles that address recyclability explicitly, and articles that explore barriers and drivers for recycling in general. Note that several papers have a broader scope than minor metals only. The articles can be grouped into four typologies based on their approach:

4 overview articles discussing the recycling system and its challenges: Lundgren (2012); Reuter et al. (2013); Tansel (2017); Tanskanen (2013)
12 articles introducing a framework or indicators for recyclability: Habib (2019); Johnson et al. (2007); Lapko et al. (2019); Mueller et al. (2017); Oguchi et al. (2011); Phillis et al. (2005); Sun et al. (2016); Ueberschaar et al. (2017); Villalba et al. (2002); Winterstetter et al. (2016); Zeng and Li (2016); Zuo et al. (2019)
6 case studies of recycling: Anctil and Fthenakis (2013); Burkhardt et al., 2020; Gusmeroli (2017); Hagelüken (2012); REMANENCE (2017); Salim et al. (2019)
3 design-oriented approaches to recycling: Chen et al. (1994); Huisman et al. (2003); Hultgren (2012)

In the second step, the collected literature was summarized using a coding approach. This approach involved the listing of barriers, success factors and challenges for recycling as described in the articles. Similar phrasings were categorized as a common aspect. For articles describing a framework, we listed the aspects and indicators that were addressed by the framework. All coded aspects were categorized based on the stage of the value chain in which they appear. After coding, the occurrence frequency of aspects was counted to create an overview of their coverage in literature, as presented in §3.1. This section also discusses the identified aspects further.

The overview of aspects was the starting point for the final step, compiling a new framework. In the framework, the identified aspects are structured in clusters of factors. From groups of closely related aspects, the most relevant one was included to avoid repetition. For instance, 'ownership' was added while narrower 'ownership shifts' was not. Each factor was linked to one or more indicators. Indicators were derived as much as possible from the literature. When no corresponding indicator was found for a factor, a new indicator was added. New indicators were chosen to connect closely to the factors.

Once the framework was established, we tested its usefulness by applying it to three case studies. The cases were selected to reflect the diversity in the development of recycling chains: platinum from car catalysts (operational recycling), neodymium from TV speaker magnets (first industrial pilots), and indium from LCD screens (research stage).

3. Aspect identification and quantification

3.1. Aspect identification

A total of 113 distinct aspects were identified in the literature, all of which are listed in Supplementary information S1. The aspects are clustered per stage of the value chain, thereby revealing how the research focus is distributed. In the analysis below, we addressed the occurrence frequency of aspects, defined as the sum of the number of unique aspects per paper.

In the reviewed articles, some value chain stages have received more attention than others. This is observed from Fig. 1 and 2, both counting the occurrence frequency of aspects. Overarching aspects, not related to a particular stage, occur with high frequency. Besides, many aspects refer to the stages of collection and recycling. Possible reasons why these three stages are overrepresented are the scope of the studies or that these stages are most critical for recyclability. Either way, a focus on these stages only would give an incomplete picture.

A further insight is provided by Fig. 2, with a division of aspects by publication type. The sets of framework and overview articles are similar in their focus, except that frameworks more often describe secondary market aspects. Frameworks address relatively few aspects of manufacturing and preprocessing. In contrast, design-oriented studies mainly focus on manufacturing and the links to preprocessing and recovery processes. Unsurprisingly, the four overview articles address a large number of aspects. In the three design-oriented articles, the occurrence frequency totaled only 17 aspects.

As highlighted in §1.2, recyclability can be approached from different angles, such as the business economic, thermodynamic, sustainability and policy perspective. Each angle yields different aspects and indicators, the major groups of which are discussed below.

3.1.1. Business economics

A frequently mentioned aspect is profitability. Moreover, eleven identified concepts are cost components. In liberal market economies, profit is indeed a dominant driving force and a profitable recycling process indicates a good recyclability. The result of a profit calculation depends on the scope of the business case. We distinguish between the business case of preprocessing and of recovery. Profitability is also a consideration for take-back schemes, when these are implemented by manufacturers under extended producer responsibility (EPR) frameworks. Consumers consider the financial aspects of their waste disposal options. In short, profitability is a relevant aspect of which is linked to various stakeholders.

Although monetary indicators are suitable for aggregation and comparison, their quantification faces challenges. To quantify business cases, an elaborate financial assessment is required. Yet for recycling routes under development, the costs are unknown, uncertain or unsettled, complicating their assessment. For example, this challenge was encountered in a case study by Mueller et al. (2017).

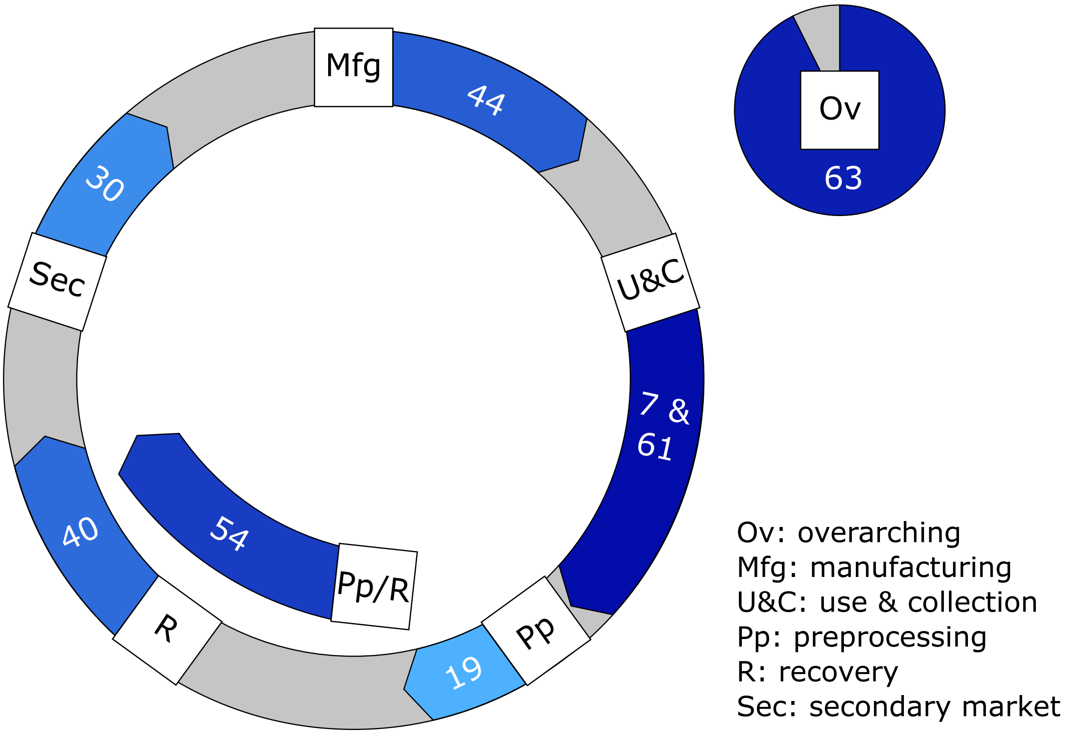


Fig. 1. Overview of aspects identified in the literature analysis. For each value chain stage, the occurrence frequency of aspects is indicated. Aspects that could not be linked to either the preprocessing or recovery process in recycling are counted under 'Pp/R'.

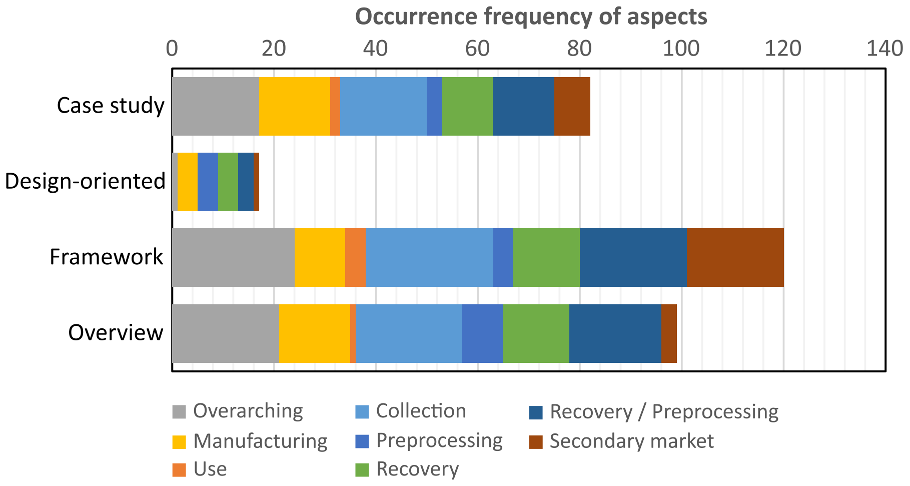


Fig. 2. Overview of aspects, per value chain stage and publication type.

3.1.2. *Thermodynamics*

An important barrier for the recycling of minor metals is their minor weight fraction in most products. This effect is exacerbated by the trend of miniaturization of components. A simple indicator for this effect is the metal concentration, as advocated by several studies (Habib, 2019; Johnson et al., 2007; Mueller et al., 2017; Oguchi et al., 2011; Winterstetter et al., 2016; Zuo et al., 2019). The concentration affects the recyclability in two ways: it increases the efforts needed to purify the metal and it increases the throughput required to recover a given mass of metal.

A related barrier is the complexity of products, which can be assessed with thermodynamic indicators for entropy. Products composed of many materials and metals require complex treatment processes, as the constituting materials are difficult to identify and their separation might require multiple steps. The literature analysis revealed that product complexity can quantified using statistical entropy, a concept originating from information theory (Rechberger and Brunner, 2002). This indicator is applied in recyclability assessments by Zeng and Li (2016) and Anctil and Fthenakis (2013). Statistical entropy analysis is also applicable in material flow analysis (MFA) studies to reveal how processes affect the dilution of materials (Rechberger and Brunner, 2002; Thiébaud et al., 2018).

Thermodynamic insights also form the basis for the element radar chart (Reuter et al., 2013). This tool indicates which metals can be separated from each other using metallurgical process, thereby identifying recoverable metals and contaminants. If contaminants accumulate in a metal or alloy, degradation can occur. An indicator for recyclability proposed by Villalba et al. (2002) is devaluation, because it reflects the reduced material value due to degradation.

3.1.3. *Design*

The 12 recyclability assessment frameworks that were reviewed in §1.2 did not address aspects related to product design and manufacturing. However, one fifth of all the analyzed articles stress that successful recycling depends on design (Burkhardt et al., 2020; Lundgren, 2012; Reuter et al., 2013; Salim et al., 2019; Tanskanen, 2013; Winterstetter et al., 2016). When manufacturers anticipate on the end-of-life (EoL) phase of their products, they apply eco-design or design for recycling, recyclability or disassembly. To help manufacturers in this process, several guidelines exist (Hultgren, 2012). These guidelines are formulated as design principles and do not indicate when DfR is considered successful, thus complicating the definition of indicators.

Nonetheless, an aspect that is fit for recyclability assessment are the joints (connections between materials and components) (Chen et al., 1994; Hultgren, 2012), because dismantling studies have revealed how joints influence the dismantling time (Desai and Mital, 2003; Kondo et al., 2003; Vanegas et al., 2018). Joints can be accounted for by classifying their separability (Reuter et al., 2013), or by counting their number or their dismantling times (Chen et al., 1994).

Another design-related aspect is the design variation of products and components. The product design variation was mentioned in multiple studies, some of which underlined the heterogeneity of products (Johnson et al., 2007; Lapko et al., 2019; REMANENCE, 2017; Reuter et al., 2013; Tanskanen, 2013) while others highlighted design changes over time (Salim et al., 2019; Ueberschaar et al., 2017). The design variation of components was only stated by Tansel (2017).

Some design guidelines aim to reduce the application of critical materials, e.g. by substitution (Chen et al., 1994). The benefit of these strategies is a reduced content of the metal in products or waste flows. At the same time, the recyclability of the remaining metal is reduced.

3.1.4. *Uncertainty*

Several studies identified aspects of recyclability that link to uncertainty, in particular uncertainty about the waste flow. The literature analysis shows that recycling requires knowledge about multiple aspects of waste: its composition (Lundgren, 2012; Reuter et al., 2013; Salim et al., 2019), its volume (Reuter et al., 2013), and product lifespan (Habib, 2019; Salim et al., 2019). Mueller et al. (2017) proposed an indicator for uncertainty, namely the confidence level of future flows.

From an organizational perspective, uncertainty can be reduced when stakeholders engage in information exchange (Gusmeroli, 2017; Lapko et al., 2019; Reuter et al., 2013; Salim et al., 2019; Tanskanen, 2013). Exchanges create more transparency and increase access to information, hence supporting recycling and well-informed decision making.

3.1.5. *Social impacts*

In all stages of the value chain, negative social effects can occur. More specifically, seven of the papers identify the issue of worker health hazards, caused by toxic substances in waste and in process chemicals (Chen et al., 1994; Hultgren, 2012; Lundgren, 2012; Mueller et al., 2017; Salim et al., 2019; Tansel, 2017; Tanskanen, 2013). The risk level of substances is indicated by regulatory lists and limits, such as the European Union (EU) RoHS and REACH Directives (Hultgren, 2012; Lundgren, 2012). These hazards are critical in informal or illegal recycling (mostly in countries where the waste was not originally generated) (Huisman et al., 2015; Hultgren, 2012) and in virgin mining and refining operations. In both cases, inadequate worker protection is an issue. Although the labor conditions vary per company, the status per country can be estimated based on the human rights conditions or labor rights conditions (Lundgren, 2012; Mueller et al., 2017).

3.1.6. Environmental impacts

Recycling is often advocated for environmental reasons, and accordingly several aspects relate to the environment. The reviewed studies address four categories of environmental impacts: climate change (Mueller et al., 2017; Salim et al., 2019; Tanskanen, 2013), human health impacts (Lundgren, 2012; Mueller et al., 2017; Tansel, 2017; Tanskanen, 2013), resource depletion (Mueller et al., 2017; Salim et al., 2019; Zuo et al., 2019), and ecosystem degradation (Mueller et al., 2017; Salim et al., 2019; Ueberschaar et al., 2017). Climate change and resource depletion receive wide attention globally. Toxicity impacts are a specific concern in metallurgical processes, both mining and recycling (Lundgren, 2012).

The overall environmental performance is quantifiable with the life cycle assessment (LCA) methodology if sufficient process details are known. The related QWERTY approach compares the environmental impact of recycling (including primary material substitution benefits) with a worst-case alternative (Huisman et al., 2003). Alternatively, some studies quantify a specific aspect such as energy consumption (Zuo et al., 2019) or greenhouse gas (GHG) emissions (Salim et al., 2019).

3.1.7. Policy

Recycling is affected by various regulations, and recycling-friendly policies can remove barriers. Several policies aim to limit the social and environmental impacts discussed above, for example by moderating the export of waste (Reuter et al., 2013). Besides, some studies identify the policy option of economic incentives (Phillis et al., 2005; Reuter et al., 2013; Salim et al., 2019). Other policies address the waste collection process, which can be approached in several ways. Examples encountered in literature include take-back requirements (Lapko et al., 2019), recycling incentives (Gusmeroli, 2017), waste collection schemes (Winterstetter et al., 2016), EPR legislation (Gusmeroli, 2017; Lundgren, 2012; Reuter et al., 2013; Salim et al., 2019; Tanskanen, 2013) or the active implementation of a collection infrastructure.

When policies are created, several strategic considerations can play a role: the economic importance of the metal (Zuo et al., 2019), its supply risk (Sun et al., 2016), worker protection (Lundgren, 2012), or the employment effects (Salim et al., 2019). The former two aspects together determine the metal criticality, an important concept in resource policies (Schrijvers et al., 2020). When a metal is labeled as critical, Sun et al. (2016) and Zuo et al. (2019) argue, its recycling is prioritized. In short, policies are shaped directly by political priorities and indirectly by the characteristics of the metal supply chain.

3.2. Aspect quantification and aggregation

A key feature of most frameworks is the use of quantitative indicators. In the 12 articles proposing a framework, 7 frameworks are centered around quantitative indicators. These indicators are for example metal concentration or product weight. Some indicators are derived with a calculation, e.g. ‘material grade’ (Zeng and Li, 2016) or environmental impact (Huisman et al., 2003). For both quantitative and qualitative frameworks, a more elaborate set of indicators can address more perspectives from §1.2, hence providing a more nuanced view.

Quantitative indicators are useful for comparisons and screening of waste flows. In comparisons, the reviewed studies interpret the indicator values relative to those of other waste flows. For example, Sun et al. (2016) assessed 11 waste flows to identify recovery opportunities for the recycling industry. A general challenge is the limited availability of quantitative information sources.

Whether aggregation is favored depends on the number of indicators. In frameworks with one or two quantitative indicators, no aggregation is applied; the results are conveniently presented in a scatter plot (Anctil and Fthenakis, 2013; Johnson et al., 2007; Oguchi et al., 2011; Villalba et al., 2002; Zeng and Li, 2016). When a framework comprises multiple indicators, their interpretation is often facilitated by grouping. Some authors combined all indicators into a single score, while others used two or three dimensions for grouping. Such aggregation was encountered in frameworks based on quantitative indicators. For instance, Sun et al. (2016) aggregate their indicators in a resource and a technology index. The framework by Sun et al. was adapted by Zuo et al. (2019), who added an environmental index. Mueller et al. (2017) defined accessibility as the overarching indicator, which aggregates multiple categories and subcategories.

Likewise, the qualitative frameworks also exhibit different structures. Some do not categorize their indicators (Gusmeroli, 2017; Lapko et al., 2019), whereas two frameworks define groups of related indicators (Ueberschaar et al., 2017; Winterstetter et al., 2016). Ueberschaar et al. (2017) based the structure of their framework on the aspects that the indicators relate to: the product, the recycling chain, and the economy. Winterstetter et al. (2016) distinguish between geological knowledge, technical feasibility and socioeconomic viability as a basis for qualitative classification. Although grouping gives a handhold for interpretation, no objective measure for a good structure exists.

When aggregating quantitative indicators, the need for weighting factors arises. Mueller et al. (2017) apply equal weight to all aspects, while recommending a more substantiated refinement. Burkhardt et al., 2020 introduce a multiplication factor for each aspect, based on expert judgement. Both Burkhardt et al., 2020 and Sun et al. (2016) calculate the product (rather than the sum) of indicators. This approach has two advantages. Indicators that are absolutely prohibitive for recycling can be assigned a value of zero, resulting in the minimum final score. Besides, weighting is only needed at the level of final scores. A drawback of multiplication is the nonlinear relation between the product and individual indicator values.

4. Proposed framework

4.1. Structure

Building on the insights from §3.1, we established a new framework. The framework structure is based on the recycling value chain stages, as shown in Fig. 3.

This visualization is inspired by the metal cycle as introduced by Reck and Rotter (2012), who mapped the anthropogenic metal flows. Fig. 3 schematically represents the supply chain stages and their contribution to a metal’s recyclability. Each stage features one or more aspects whose performance is scored using underlying indicators. In the diagram, the scores are indicated with a color gradient.

The framework, including factors and indicators, is displayed in Fig. 4. By means of a dashed outline, the diagram highlights factors and indicators that have not been used before in recyclability frameworks. In §4.2, the underlying factors are described, while §4.3 presents quantitative aspects of the approach.

4.2. Factors & indicators

Overarching: A number of factors are not connected to any of the value chain stages in particular; these are classified as overarching factors. Two overarching factors, economic drivers and uncertainty, are both essential for making investment decisions. The other factors included here are the broader social benefits and supply chain alignment.

- The first of two economic drivers is economies of scale, which is measured as the mass of the annual waste flow. Transport costs and sorting capacity scale with this indicator. Metallurgical recovery plants require a throughput of about 100 kt/a (Reuter et al., 2013). Large waste volumes could also be beneficial for other processes throughout the recycling value chain, through enhanced learning effects. A second economic driver are fiscal incentives, i.e. policies that increase the profitability of recycling compared to alternatives.

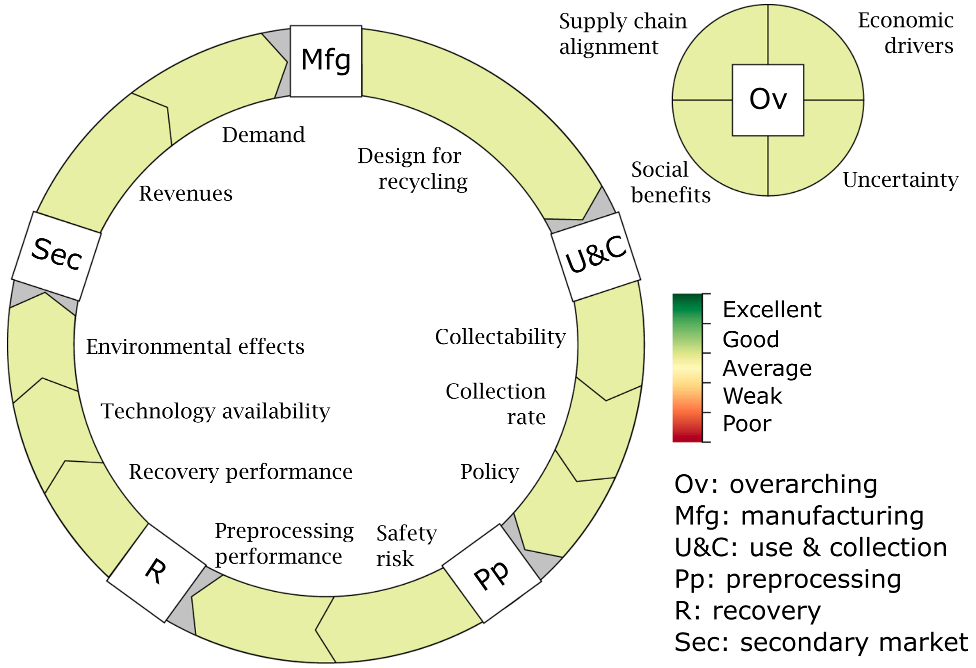


Fig. 3. The framework structure, matching the stages of the recycling value chain.

Possible incentives are subsidies, or taxes on waste disposal and virgin material use.

- The major uncertainty of future flows is indicated by the standard deviation of the estimated waste quantity. For investments with a longer payback period, the uncertainty of flows in the further future is relevant. Therefore, the uncertainty up to the end of the investment horizon of recyclers is considered.
- Social benefits address the labor conditions along the primary metal supply chain. Issues arising here can incentivize recycling. On the one hand, incidents correlate with the health and safety hazard of the current practice, which is judged based on hazardous substances. On the other hand, incidents arise in poor labor rights conditions, as quantified by the labor rights indicator (Kucera and Sari, 2020) of the country that hosts the waste treatment or mining process.
- Supply chain alignment refers to the extent to which actors cooperate and engage in collective planning. This social factor is captured by information exchange, which refers to information relevant to recycling. It is quantified as the fraction of actors involved in exchanges.

Manufacturing: The manufacturer of a product plays a role by making design decisions that affect dismantling. This role is expressed in design for recycling, which comprises three important design parameters.

- Design variation is included because it influences how sophisticated the sorting and dismantling process should be. Heterogeneous waste flows are more difficult to process. The variation is assessed using two indicators, for product design variation and for component design variation. These indicators reflect the number of different designs of products and components available on the market. For certain products, these indicators can be connected.
- Dispersion refers to miniaturization and the small volumes of metal in products. The indicator used here is the metal content per component.
- The type of joints affect the dismantling effort. A preference order is used to rank the joints (based on Kondo et al., 2003; van Schaik and Reuter, 2012) from least to most preferable: Coating, paint, adhesive, glue, screws, encasing, plugs, snap fitting.

Use & Collection: The use and collection phase are closely linked because in both phases, the product owners play a key role. Their contribution to successful loop closure is expressed by the collection rate. Two factors that support collection are included as well: collectability (the ease of collection) and policy.

- Three product-related aspects are included to address the collectability: ownership, product weight and quantity. The type of product owner determines feasible collection network structures. When the manufacturer remains owner of the product in a service contract structure, their responsibility for EoL collection increases. When the users are companies, the collection process is relatively simple (Knemeyer et al., 2002), in particular for low numbers of companies. In the case of consumers, collection depends on the presence of a visible and extensive collection infrastructure, the creation of which requires significant efforts (Tanskanen, 2013). The structure of the collection network is largely determined by the combination of product weight and quantity. Heavy products are less likely to be disposed of incorrectly by consumers (Oguchi et al., 2011). For products that are disposed frequently, the investment in collection facilities is lower per product (Tanskanen, 2013).
- The collection rate depends on the collection participation, as indicated by the fraction of products collected. The prospects of future collection are based on consumer awareness and infrastructure density. Awareness is indicated by the fraction of consumers that is aware of separate waste collection infrastructure. The infrastructure density is characterized by the distance between collection points. These two indicators are mostly applicable to consumer goods.
- Collection is affected by policies, of which two major types are included here. EPR is a scheme that makes manufacturers responsible for correct collection and treatment of their products. Export restrictions aim to prevent undesired waste export to countries that lack effective recycling facilities. These restrictions are most effective in combination with law enforcement to counteract illegal export (Huisman et al., 2015).

Preprocessing: This stage comprises all manual and mechanical processing steps in a sorting or recycling plant. It is characterized by its safety risk and its technical performance.

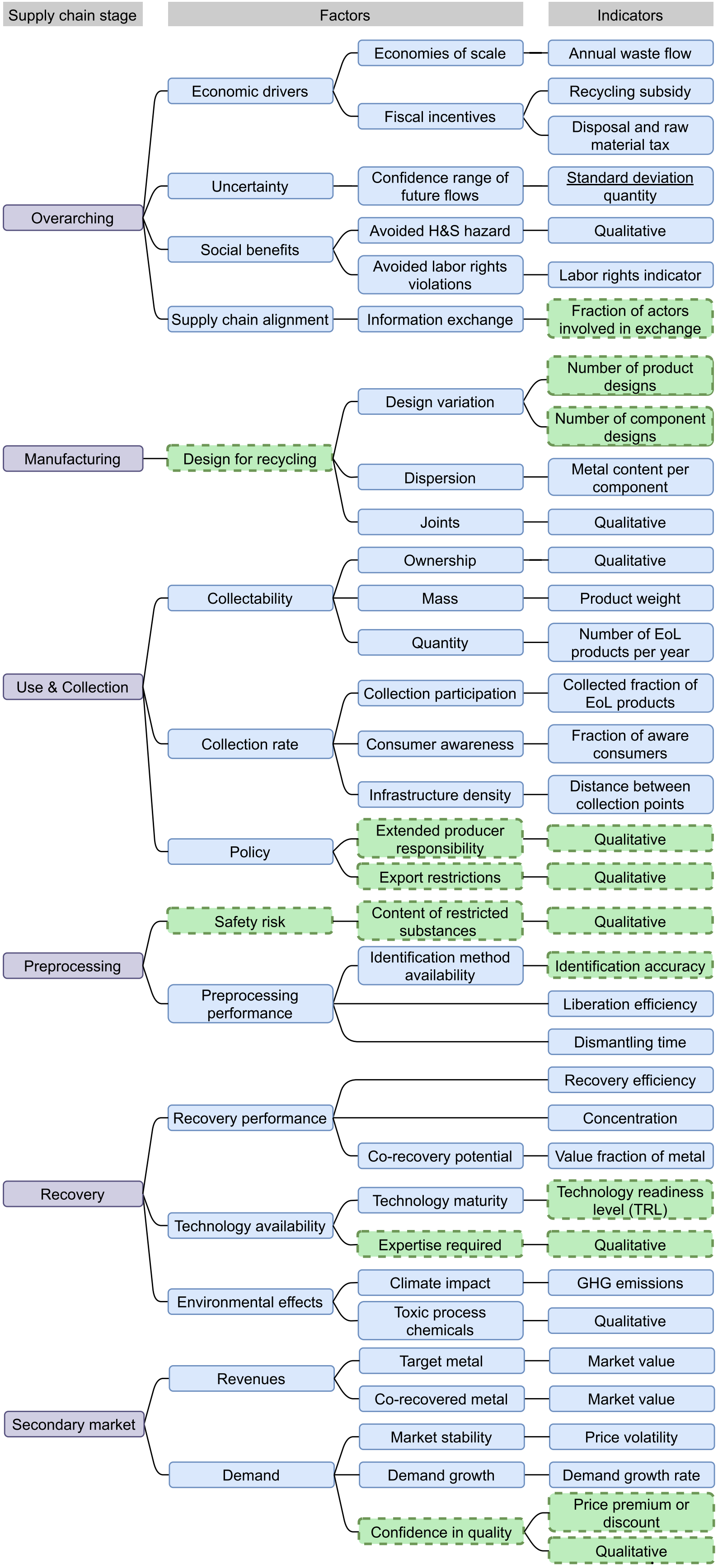


Fig. 4. The recyclability assessment framework and its structure, clustering by value chain stages. New indicators—not found in existing frameworks—are indicated by a dashed outline. H&S: Health and safety; GHG: greenhouse gas.

- The safety risk is indicated by the content of restricted substances in waste. Toxic or harmful substances create H&S risks, in particular in the preprocessing stage. This calls for safety measures to protect workers. In addition, safety regulations (RoHS and REACH in the EU) demand that a recycling company invests in e.g. certification and permitting procedures.
- The preprocessing performance is assessed by three indicators. First, the identification accuracy indicates the maturity and availability of methods to identify components or devices in the waste flow. This is an essential preprocessing step when only specific components contain the metal of interest (Burkhardt et al., 2020; Habib, 2019; Ueberschaar et al., 2017). The second indicator is the liberation efficiency, i.e. the fraction of target metal that enters the recovery process. A trade-off exists between the liberation efficiency, purity after liberation and preprocessing efforts (Reuter et al., 2013). Third, dismantling needs labor inputs from either humans or robots. Both can have a substantial effect on the economic feasibility. A good indicator, even in a pilot phase, is the dismantling time, because it indicates the complexity of the task.

Recovery: Recovery refers to the metallurgical processes that separate and purify the metal of interest. Similar to preprocessing, also here one of the factors is technical performance. In addition, the technology availability and the environmental performance are considered.

- The performance of the recovery is indicated by its efficiency, which can be quantified in lab or pilot experiments. Besides, an indicator is included to address the performance potential, i.e. the metal concentration in the recovery input (after preprocessing). When the concentration is low, high recovery is either impossible or costly. A third factor of performance is the potential co-recovery of metals within a product, which can be assessed using an element radar chart (Reuter et al., 2013). This tool indicates which metals are recoverable in each metallurgical process. An indicator for co-recovery is the fraction of metals by value that have compatible extraction. This accounts for product compositions and differences in metal values (Reuter et al., 2013; Zuo et al., 2019).
- In particular for recovery, sufficiently developed technologies are often missing. Therefore, the technology availability is assessed using the indicators of technology readiness level and expertise required. When more expertise is required, it is more challenging to find competent personnel and to operate the process correctly.
- The estimated environmental effects of recycling can be known from prospective LCA studies (Arvidsson et al., 2018). The environmental burdens are addressed by two factors: climate impact and toxic process chemicals. It is advised to focus on the environmental impacts of the recovery stage, because this stage is a hotspot for emissions and is most variable.

Secondary market: The final link that closes a supply chain loop is the secondary market, where manufacturers purchase recovered metals. This transaction is characterized by the revenues. A second factor is the demand, which addresses the extent of 'pull' from the market.

- Revenues are generated by selling the recovered target metal and optionally co-recovered metals. An indication of each is obtained from the average market price. The indicator is expressed per ton of waste, reflecting that the waste input determines the processing capacity.
- The demand is assessed by three factors. The first, market stability, is characterized by a low price volatility. Many minor metal markets show a high price volatility (DERA, 2019), resulting in uncertain recycling business cases uncertain and reluctant investors. Price volatility intensifies the investment risk created by long payback times. On the other hand, more mature recycling chains offer the advantage of a more constantly priced resource. The second aspect is the demand growth rate (Lapko et al., 2019), because it increases the risk of temporary shortages whereas recycling offers a more constant supply. In addition, an expanding market offers a growing number of potential clients. Third, the confidence of clients is indicated by the price premium or discount. For emerging recyclers, it is challenging to gain the trust of potential clients, mainly related to the recycled product quality (Salim et al., 2019). On the other hand, clients might be willing to pay a premium if they value the sustainability of recycled resources.

4.3. *Quantification and aggregation*

The proposed framework intends to facilitate the comparison and ranking of different waste flows, and to this end it includes an approach for determining recyclability scores. These scores are calculated for each factor based on the corresponding quantitative or qualitative indicators, as illustrated in Fig. 5. For qualitative indicators, we use a rating scale, in which 0–1 indicates a poor and 4–5 indicates an excellent performance. These scales can benefit from a frame of reference based on different cases. Quantitative indicators are normalized relative to minimum and maximum possible indicator values, and then translated to a 0–5 scale as well.

It is possible to determine the score of aspects higher in the hierarchical structure of the framework (see Fig. 4) through aggregation. Aggregated scores are calculated as the average of underlying indicators. It is possible to apply differentiated weighting factors based on the relative importance of factors, although for simplicity the present study does not differentiate.

In practice, the information to determine indicator values can be unavailable. These undefined indicators are disregarded when determining the average scores. For instance, when the collection participation is unknown, the score for collection rate is only based on the scores for consumer awareness and collection infrastructure density.

5. Case studies

5.1. *Case study scope*

This section features three case studies to illustrate what insights can be derived when the framework is applied. The case studies and their scope are outlined in Table 1. To support the interpretation of the findings, they are presented in the form of a diagram in Fig. 6.

5.2. *Case study data*

For all three case studies, we collected data to evaluate the indicator set. Data sources include MFA studies, indicator reports (DERA, 2019; Kucera and Sari, 2020) and qualitative information from literature. Scores on a 0–5-scale were calculated according to the proposed method and formulas (§4.3, Supplementary information S2.2). The results are described in §5.3, while underlying data and assumptions are detailed in Supplementary information S3.

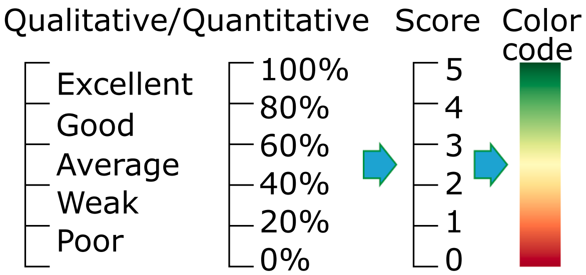
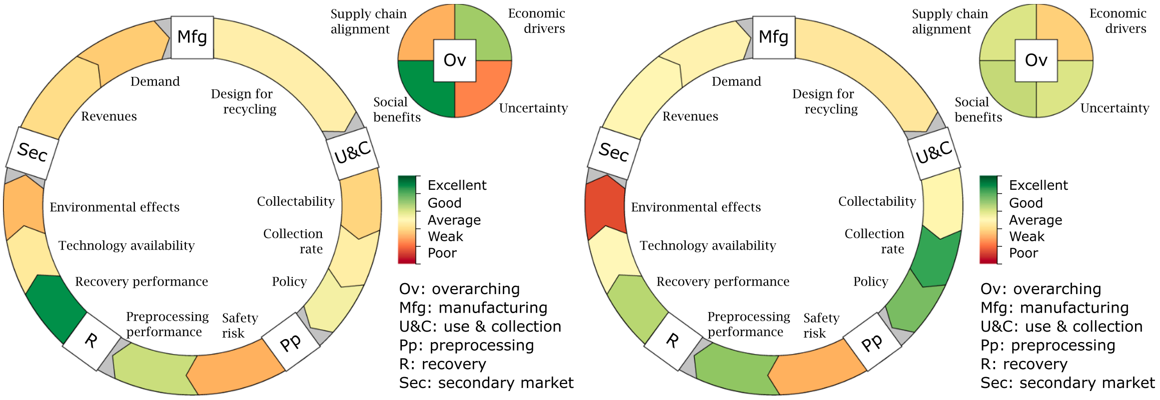


Fig. 5. Example of mapping indicator values to scores.

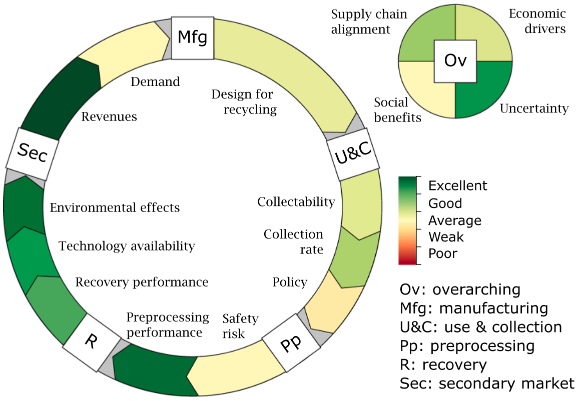
Table 1
Definition and scope of case studies.

Case study metal	Product category	Recycling technology	Geography
a) Neodymium	TV speakers	hydrometallurgy	EU-28
b) Indium	LCD screens (TVs, monitors, laptops)	hydrometallurgy	Switzerland
c) Platinum	car catalytic converters	plasma arc furnace smelting using iron collection	EU-28



(a) Neodymium from TV speakers

(b) Indium from LCD screens



(c) Platinum from catalytic converters

Fig. 6. Recyclability scores of three case studies.

5.3. *Case study results*

Fig. 6 illustrates that stages with higher scores indicate drivers, while low scores indicate bottlenecks for recycling. The visual representation with color coding allows to compare the case studies and identify those with a high recyclability.

We find that the Nd recycling case has on average the lowest indicator scores (Fig. 6(a)). In each stage, there is room for improvement, with the most notable barriers found among the overarching factors. Potential drivers for successful recycling are the social benefits and the recovery and preprocessing performance.

In contrast, the indium case study (Fig. 6(b)) reveals three major bottlenecks while other aspects are moderately positive. One bottleneck is the environmental impact, as several studies indicate that indium recycling causes a higher impact than primary mining (Böni et al., 2015). This barrier is linked to the low concentration of indium in screens. The other barriers are the safety risk from hazardous substances, and limited economies of scale.

Fig. 6 (c) shows that platinum recycling from car catalysts has almost no barriers, which is in line with the worldwide EoL recycling rate of over 50% (Graedel et al., 2011). Given the maturity of platinum recycling compared to emerging recycling industries, policy incentives are less relevant. While e.g. subsidies are useful for emerging technologies, they are no longer essential when a recycling system has been established. Room for improvement is identified in the export regulations, because this policy can be enforced better (Mehlhart et al., 2017).

5.4. *Case study discussion*

Generally, in the case studies we successfully quantified most indicators using publicly available data. As expected for early-stage assessments, some input data for case a) and b) entailed high uncertainty. For example, no quantitative data was found for the information exchange and the fraction of aware consumers. Still, the indicator set allowed to draw an indicative picture of the recyclability in each case.

Case b) indicated the benefit of an iterative approach. Within Switzerland, a limited economy of scale can be attained, which can be improved by enlarging the geographic scope of the analysis. With the scope extension, other indicators also change, so understanding the net effect on the recyclability requires a re-assessment. In addition, each further iteration can refine the quantitative input data.

Because the selected case studies are diverse, ranking them based on overall recyclability was not our goal. A ranking would require to trade-off the multitude of factors. In contrast, a ranking of alternatives will be easier in practical settings, where alternatives only differ on some aspects. An example is the comparison of wastes as inputs for a platinum recycling plant. These wastes will have similar scores for the factors related to demand and recovery technology. Another example is the comparison of robotic and manual dismantling, in which case the preprocessing and recovery factors are relevant. In both examples, a subset of indicators is used which simplifies the interpretation.

The comparison of the three case studies shows a high variability in recyclability characteristics for different metals and different applications. The scores ranged from mostly good to predominantly weak. In addition, differences were revealed as to which value chain stages present bottlenecks for recycling. Therefore, we conclude that a low recyclability can have several causes, which require different actions to overcome.

6. Discussion & conclusions

This paper aimed to improve the conceptual understanding of minor metal recyclability. A systematic screening of available literature provided and overview of barriers and drivers for recycling. Based on this overview a framework was proposed, which provides a structured view on the factors that determine recyclability. To our knowledge, this framework is unique in addressing minor metals specifically, as well as addressing all stages of the recycling chain. The focus on minor metals is reflected by the indicator set. Compared to other materials and metals, minor metals have a high *uncertainty* of future flows, a high degree of *dispersion* and a low *concentration* in products. Because of these properties, important process-related factors are the *identification accuracy* and the *expertise required*. Finally, the relatively high metal price volatility is included under *market stability*.

Next to providing conceptual understanding of recycling systems, the framework is a step towards an operational assessment of recyclability. The framework is useful for analyzing various recycling systems, as demonstrated in three case studies. The framework can be applied for comparative analyses between minor metals, waste flows, or between recycling technologies. For these comparisons, a geographic scope must be defined, since several factors are location-dependent. It is also possible to compare recyclability between countries, which could help to identify a location with favorable conditions for recycling.

Contrasting the framework to other recently published frameworks, a few differences stand out. One difference is in the type of the final outcome. Other frameworks yield an outcome that is aggregated to one (Mueller et al., 2017), two (Sun et al., 2016) or three (Zuo et al., 2019) dimensions. These overall scores allow for prioritization of numerous alternatives, but do not allow to pinpoint value chain steps with bottlenecks. The latter is a strength of our framework, due to the grouping of factors by value chain step. The hierarchical grouping shows the underlying factors as in Fig. 3, enabling to identify bottlenecks.

A notable difference with most other frameworks is the absence of monetary indicators. This choice is motivated by the uncertainty in business cases, which is particularly high in the case of minor metals (see §3.1.1). Instead, the proposed framework does include important cost drivers. This approach is similar to the way in which Sun et al. (2016) used size reduction as a proxy for preprocessing costs.

The proposed indicator set is applicable to end-of-life recycling in most regions. The framework is less applicable to pre-consumer scrap, for which indicators of use and pre-processing could be irrelevant. Besides, some adjustments might be needed for application in developing countries. This limitation stems from a bias in the reviewed literature. Although none of the studies states the geographic demarcation, they are geared towards developed countries. Consequently, the social aspects of recycling might need different interpretation. For instance, a lack of H&S regulations influences the social benefits of recycling. Note that the proposed indicators are primarily applicable in early stages of development. For more advanced recycling systems, more detailed indicators can be added. These indicators use information from e.g. financial assessments and stakeholder surveys.

Several factors of recyclability are interlinked, as it is impossible to isolate independent factors. These interdependencies and causal loops can be investigated in future research using system dynamics models (Glöser et al., 2013). This enables to determine weighting factors that express the importance of each indicator. It is therefore recommended to investigate the system dynamics, using the presented framework as a basis.

Another future research opportunity is to use the recyclability assessment in parallel with MFA. The latter highlights current flows and losses and provides quantitative input to some indicators. This was demonstrated in the case studies, that referenced MFA studies. In turn, the recyclability indicators highlight the relevance of flows for recycling. In this way, both analyses complement and enrich each other.

The framework is particularly helpful to close the cycles of minor metals, as it facilitates recyclability assessment in both the recycling industry and by policy makers. The presented framework and indicator set can be used as guidance for three main decisions: what waste flow to address, which technologies to apply and where to locate recycling operations. Besides, the framework assists policy makers to identify and resolve bottlenecks in recycling systems. To conclude, this framework paves the way for a more circular economy for metals that might be minor in volume, but major in economic importance.

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CRediT authorship contribution statement

Sander S. van Nielen: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **René Kleijn:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Benjamin Sprecher:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Brenda Miranda Xicotencatl:** Conceptualization, Writing – review & editing. **Arnold Tukker:** Writing – review & editing.

Declaration of Competing Interest

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

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.resconrec.2021.105881

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