

EMPOWERING FOUNDRIES FOR SUSTAINABILITY: A USER-FRIENDLY ECO-DESIGN TOOL FOR ENVIRONMENTAL SELF-ASSESSMENT

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ABSTRACT

Given the role of aluminum as a strategic resource for several decarbonization strategies, its global demand has experienced an exponential growth. However, aluminum production remains highly energy-intensive and environmentally impactful. Our objective is therefore to support aluminum foundries in addressing the challenge of reducing their environmental burden. For this purpose, this study introduces a software (named Eco-design tool) developed for Italian small and medium aluminum foundries. The tool enables self-assessment of environmental performance based on the Life Cycle Assessment (LCA) methodology, which evaluates the impacts of the foundry process – including emissions, energy use and waste management. Through a user-friendly interface, the tool collects site-specific data from seven production phases to calculate key environmental indicators. The main output is a preliminary environmental profile that helps companies identify critical impact areas and supports informed decision-making, strategic planning and continuous improvement, helping companies align with circular economy principles and reduce environmental impacts. The Eco-design tool is particularly valuable for small and medium-sized companies lacking the resources for full-scale LCA studies and can guide them toward environmental certifications. Future work will focus on expanding the dataset, improving usability, and validating the tool across a broader sample of foundries.

1. INTRODUCTION

In recent years, sustainability has become a crucial objective for companies aiming to maintain their competitiveness. Industries face constant pressure to enhance the environmental performance of their products and manufacturing processes by reducing waste production and preventing pollutant emissions (Appolloni et al., 2022). Aluminum production is a strategic asset to boost environmental sustainability in several industrial sectors, such as the automotive one (Pauliuk, 2018). In fact, as a major metal, it enables transportation, communication, housing, and an infinite number of products and services (Elshkaki et al., 2018). However, this industry is encountering multiple challenges due to intensifying global competition, strict environmental regulations, emissions, and waste issues, all of which affect sustainability performance (Madan and Singh, 2023). Among these challenges, the high demand of bauxite, classified as a critical raw material by the European Commission (European Commission, 2023), is particularly significant as it is unlikely to be sustainably satisfied by the known reserves (Xiao et al., 2023). Moreover, the production of primary aluminum is hugely energy intensive

compared to other metals, thus affecting the environmental performance of aluminum products. Hence, recycling aluminum becomes strategic to reduce its environmental impacts (Raabe et al., 2022).

Given this context, foundries are under increasing pressure to quantify and to improve their environmental performance, yet often lack the tools and resources to do so effectively.

Life Cycle Assessment (LCA) has emerged as a key methodology for quantifying the environmental impact of products and processes in the aluminum industry. In fact, it is frequently used in scientific literature to quantify the environmental performance of primary and secondary aluminum (Liu and Müller, 2012) and has been widely endorsed by sectoral associations such as the European Aluminium Association (EAA, 2024), the International Aluminium Institute (IAI, 2023), and the Aluminum Association (AA, 2023). LCA offers a comprehensive “cradle-to-gate” or “cradle-to-grave” perspective, allowing foundries to evaluate multiple environmental impact categories, such as Climate Change, Acidification, and Resource depletion. This holistic approach makes LCA particularly suitable for aluminum foundries (Milovanoff et al., 2021), where environmental

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burdens are spread across upstream raw material extraction, energy-intensive production, and downstream waste management (Rossi et al., 2025). Furthermore, the recent adoption of the Product Environmental Footprint (PEF) approach, including category rules for metals (European Commission, 2016; European Aluminium, 2022), further strengthens LCA's relevance by enhancing consistency and comparability across assessments.

Despite its advantages, a major limitation of LCA in the aluminum sector remains the scarcity of site-specific primary data. As noted by several studies (Brogaard et al., 2014; Luthin et al., 2021), LCA models often rely on generic industry databases, which may not reflect regional or national production conditions. This lack of geographical representativeness can lead to misleading conclusions and hinder the development of tailored sustainability strategies. While some authors have conducted LCA based on primary data collected at specific sites – such as Grimaud et al., (2018) who focused their study on an aluminum recycling plant located in France, and of Liu et al., (2021) and Salonitis et al., (2016) who have investigated the energy consumption of aluminum production in two aluminum production and die-casting sites in United Kingdom – most studies still depend on secondary datasets.

Thus, since several LCA studies available in the literature are based on industry-generic databases which are not fully representative of the geographical context in which the production site is located, Rossi et al. (2025) strongly encourage future research to fill this gap and overcome this issue by developing country- or regional- specific databases. To overcome this limitation, recent research efforts - such as the GRINS - "Growing Resilient, INclusive and Sustainable" project funded under the EU NextGenerationEU initiative - have focused on collecting and processing quantitative data from Italian aluminum foundries to build nationally representative datasets (Grins Foundation, 2023).

Another promising solution for improving geographical representativeness of LCA analyses is the development of digital tools and calculators tailored to specific industrial contexts. These platforms allow foundries to enter their own operational data and receive an immediate estimate of their environmental footprint. This is especially relevant for small and medium-sized enterprises (SMEs), which dominate the Italian foundry sector (Assofond, 2025), and often lack the resources – in terms of time, budget, organizational capacity, or knowledge – to perform full LCA studies (Testa et al., 2017; Singh et al., 2021). Moreover, since the last decade, sustainability assessment tools have been designed for multinational or large firms but, typically, they are not suitable for SMEs (Gómez-Garza et al., 2023; Ortiz et al., 2023). While these tools do not replace the expertise required for certified environmental labeling (e.g., EPDs, EU Ecolabel, or Made Green in Italy (MGI)), they do offer a low-cost, accessible entry point into sustainability assessment and strategic decision-making.

Given this background, the specific research gap addressed by this study concerns the lack of practical, site-specific, and user-friendly tools that support Italian aluminum foundries - especially SMEs - in conducting pre-

liminary environmental self-assessments. Thus, the aim of this paper is to fill this gap presenting a novel aluminum Eco-design tool developed within the framework of the "BRIEF - Biorobotics Research and Innovation Engineering Facilities" project, funded by the Italian National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment Plan 3.1 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU, providing a discussion on its possible managerial implications for the Italian aluminum foundries. In particular, this paper is focused on presenting the managerial implications of the tool, that enables companies to estimate their environmental impacts based on primary and site-specific data, offering managers a practical means to align with circular economy goals and anticipate environmental certification requirements.

2. METHODS

The Eco-design tool presented here has been developed in collaboration with the Italian Foundry Industrial Association-Assofond (Assofond, 2025). Such self-assessment tool is a calculator based on LCA that allows aluminum foundries to perform a screening calculation of their environmental impacts. The foundry process is composed of 7 steps, including melting, casting, molding, piece removal, finishing, thermal treatments, quality checks. The development of the calculator has followed 3 stages: 1) Data collection, 2) Impact factors quantification, and 3) Eco-design tool development.

Figure 1 is a flowchart which presents an overview of the methodology, combining a summary of the three stages of Eco-design tool development (shown in the top part of the Figure) with the seven steps of the foundry process (shown in the bottom section). The figure also highlights that the tool's LCA results are calculated and displayed for each step of the process.

Concerning 1) Data collection phase, a checklist has been designed and sent with the support of Assofond to hundreds of foundries located throughout the Italian territory during the GRINS project. The checklist is an excel spreadsheet in which each module corresponds to one of the stages of the foundry process. Every module contains tables where materials and energy flows are listed row-by-row, and the corresponding amounts have to be filled in the columns, together with comments, notes, and transport distances. The materials and energy flows are the following:

- Ingots (primary and secondary);
- Alloy elements;
- Modifying agents;
- Refining agents;
- Fluxing agents;
- Degassing agents (e.g. nitrogen, argon);
- Fuels (e.g. natural gas);
- Waste (slag, dust, refractories);
- Electricity (e.g. from renewable or fossil sources, grid mix);
- Moulds and cores (including sand, resins, and other additives);

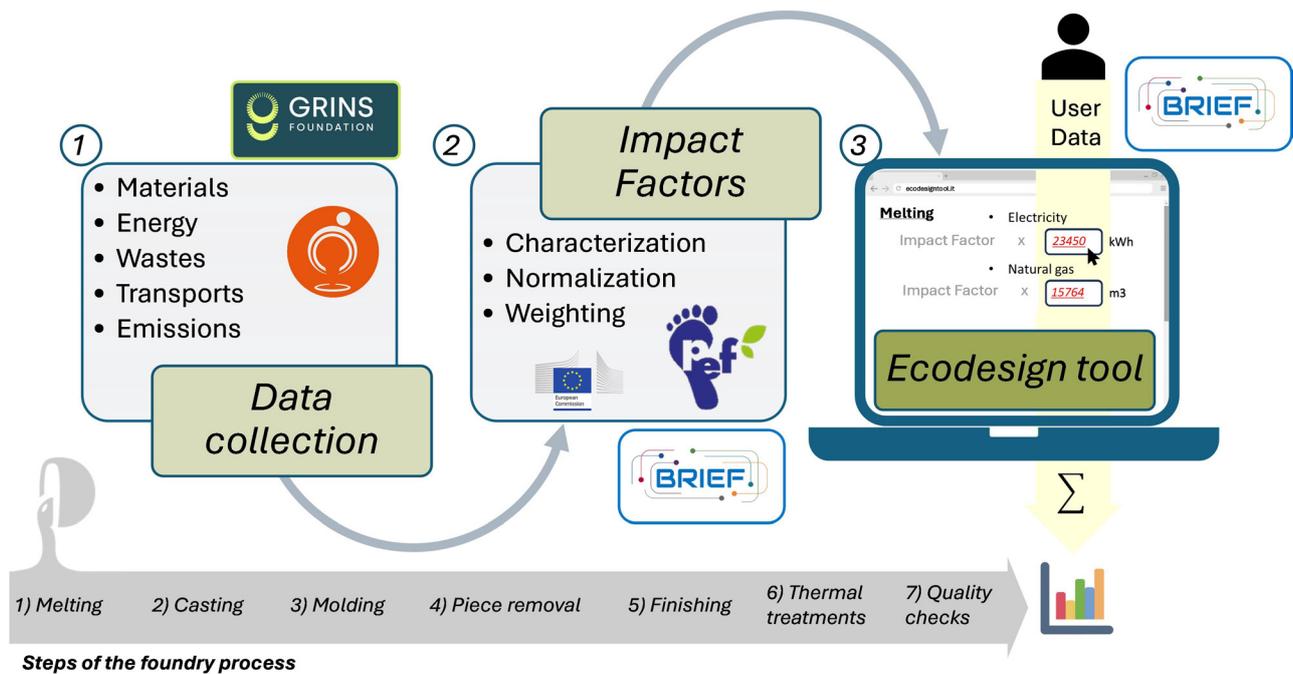


FIGURE 1: Sketch of the methodology followed to define the Eco-design tool for aluminium foundries.

- Water;
- Direct emissions.

The checklist has been filled by 15 foundries with quantitative data and descriptions about the materials consumed over the 7 steps of the process, as well as energy consumption, direct emissions to the atmosphere, transports and waste management (Figure 1). Firstly, 4 volunteer pioneer foundries have tested the effectiveness of the checklist; then, other 11 factories filled the final version. Since energy and material flows vary significantly from foundry to foundry, the checklist has been developed in excel format using a flexible and generic classification of the inputs and outputs of the process. For instance, with the support of Assofond, materials input in the melting furnace have been classified in the classes listed in the above bullet point list. Based on this general classification, foundries could fill the checklist with more specific information: for example, they could add aluminum EN AC-45300 alloy ingots for the class 'ingots', copper for the 'alloy elements', or aluminum-titanium-boron for the 'refining agents'. A similar approach has been used to classify energy sources (e.g. most of foundries declared the use of natural gas, gasoline, and liquefied petroleum gas) and waste recycling and disposal (e.g. most of foundries reported disposing refractory waste and recycling dross and dust).

As illustrated in Figure 1 (more precisely from first box on the left), based on the information collected from the respondent foundries, it has been possible to identify which materials and energy sources are consumed by the foundries and which waste and emissions are produced. In the context of the BRIEF project, environmental impact factors were associated with these energy and materials flows following the LCA approach (central box of Figure 1). Impact factors calculation is based on the PEF meth-

od: this implies that the use of secondary materials and the recycling of waste are modeled using the Circular Footprint Formula, in accordance with PEF recommendations for parameter setting. Using the software SimaPro version 9.6, the background database ecoinvent 3.9.1 cut-off version (Frischknecht et al. 2005), and the Life Cycle Impact Assessment (LCIA) method Environmental Footprint 3.1 (Bassi et al., 2023), 16 environmental impact indicators are calculated (including characterization, normalization and weighting steps). For instance, in case foundries add copper as alloying element, the corresponding impact factor is calculated as the environmental impacts of 1 kilogram of copper from the ecoinvent dataset "market for copper, cathode". Even though the eco-design tool provides the LCIA results considering all 16 impact categories, it is worth mentioning that the most relevant impact categories in the metals sector are, according to (Santero and Hendry, 2016):

- Climate Change: measures the effects of GHG emissions to Climate Change [kgCO₂ eq];
- Acidification: measures the effects of acidic substances on the environment, particularly on soil and water, which can disrupt ecosystems and harm living organisms [mol H⁺ eq];
- Eutrophication: measures the level of nutrients released into water bodies through human activities, leading to excessive algae growth, oxygen depletion, and ecological imbalances [kg P eq];
- Photochemical ozone formation: measures the emissions of pollutants, such as nitrogen oxides which contribute to the formation of ground-level ozone and smog, impacting human health and the environment [kg NMVOC eq];
- Ozone depletion: evaluates the release of substances, such as chlorofluorocarbons (CFCs), that deplete the

ozone layer in the stratosphere, allowing harmful ultra-violet radiation to reach the Earth's surface [kg CFC11 eq].

In LCIA, the characterization step quantifies the contribution of different emissions and resource uses to environmental impact categories, expressing – for instance - all greenhouse gas emissions as CO₂-equivalents. Normalization contextualizes these impacts by comparing them to a reference, for instance the total environmental load of a person or a region, highlighting their relative significance. Weighting assigns relative importance to different impact categories, enabling their aggregation into a single score to support decision-making (Hauschild et al., 2018).

The developed Eco-design tool is composed of a foreground and a background layer (right box of Figure 1) and it is based on the environmental impact factors associated with the materials and energy flows related to the foundry process that were identified in the context of the GRINS project. The foreground layer is a graphical user interface in which the users can enter their data; the background layer is composed of mathematical formulas – invisible for the user - converting input data into output results.

In the foreground layer, users can enter site-specific values for the foundry under investigation. For instance, in case the annual copper additions amount to '100' kg, the users are required to insert this value in the calculator. In the background layer, the amounts entered by the user are multiplied by the corresponding impact factors. The calculation is performed for each of the steps of the foundry process which are inserted by the user. The impacts of all the relevant steps are then summed up and the final out-

put provided by the Eco-design tool is the environmental burden of the foundry related to 1 kg of aluminium produced, i.e. the functional unit. Following up with the example above, the amount '100' kg of copper is multiplied by the environmental impact of 1 kg of copper resulting from the dataset "market for copper, cathode", i.e. 6.86 kg CO₂ eq / kg copper. A beta-version of the calculator is now online and available for testing by the aluminium foundries associated with Assofond. Seven foundries have provided feedback on the tool: five of them had previously participated in the GRINS data collection campaign, while the other two did not contribute with data in the initial phase. Interestingly, all the foundries that had provided data in GRINS have now considered the tool developed in BRIEF as complete and comprehensive; their main concerns were focused instead on the graphical user interface. In contrast, the 2 foundries that had not contributed with data to the development of the calculator, identified some missing materials and energy flows. The next steps in the development of the tool will involve integrating additional data collected from the testers and expanding the access to the calculator across all foundries affiliated with Assofond. Figure 2 summarizes the geographical distribution of the foundries that contributed to the data collection and the tool validation. These companies are concentrated in the center and north of Italy, thus reflecting the actual distribution of Italian aluminum foundries according to Assofond. In Figure 2, blue labels indicate foundries that participated only in data collection, red labels indicate those involved only in tool validation, and yellow labels indicate participation in both parts of the Eco-design tool development.

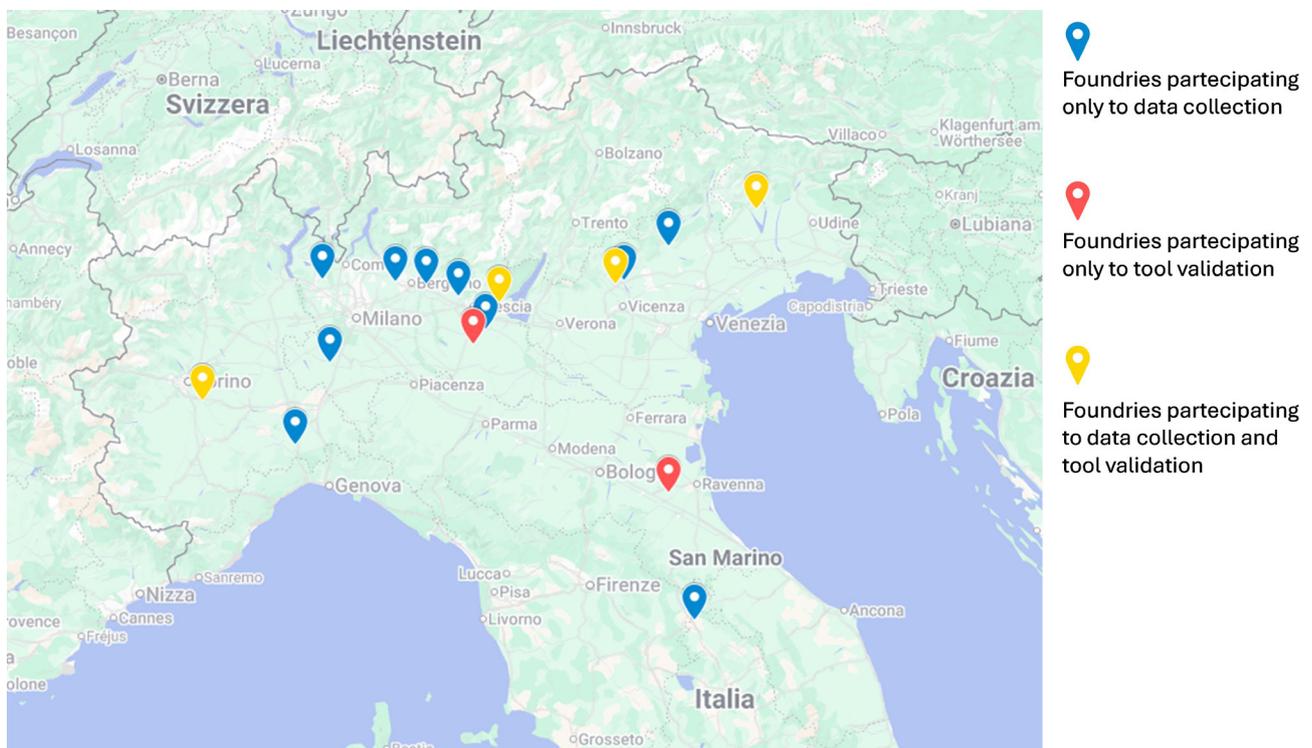


FIGURE 2: Geographical distribution of the foundries participating to data collection and tool validation.

3. RESULTS AND DISCUSSION

The Eco-design tool (developed in Italian) has a modular structure, as illustrated in the dashboard shown in Figure 3. The dashboard becomes accessible after creating a profile on a portal (available via a specific link) and consists of three panels. The left panel allows users to navigate between the modules of the tool, which correspond to different phases of the foundry process. The central panel presents a list of sections where users enter quantitative data or select an option from a dropdown menu (e.g., specifying the means of transport). The right panel contains hyperlinks to all sections within the current module.

Once the whole questionnaire is filled, the user will be able to display the results as numeric tables containing the impact of the process and the contribution of all the 7 steps. Two types of charts are also available: a stacked columns chart (Figure 4 as illustrative example) expressing the contribution of the modules to each midpoint impact category, and a pie chart summarizing the contribution of each impact category to the overall environmental impact (also called single score), calculated through normalization and weighting. The Eco-design tool has been tested by Assofond and 7 pioneer foundries who have proposed changes before the release of the final version of the Eco-design tool. The applicability of the tool has been significantly enhanced through the contributions of these foundries. Five new material types have been added, broadening the scope of analyses. Moreover, based on the feedback received, the tool now allows results to be exported in an editable Excel

format, making it easier to adapt and use the data from a managerial perspective. Additionally, the tool automatically generates a technical report, which managers can leverage to present results to customers or during internal meetings.

Figure 4 presents the results from a foundry that participated in the tool's development. The real-world case study presented here analyzes a process consisting of melting, casting, piece removal, finishing, and quality checks. Figure 4a shows that, for the most relevant impact categories discussed in Section 2, the melting phase is the primary environmental hotspot. Casting and finishing contribute similar levels of environmental impact (depending on the impact category considered), while quality checks are only significant for the indicator Marine eutrophication. Figure 4b highlights that Climate change is the most critical impact category overall. From an eco-design perspective, this indicates that improving resource efficiency in the melting phase offers the greatest potential for reducing the environmental impacts of the entire process. The tool's accuracy was validated by comparing its results with those generated by the professional LCA software SimaPro. The differences were found to be below 1%, confirming the tool's high level of accuracy. However, in order to guarantee high accuracy, high quality data entry from the user is also required.

We have seen that, while LCA is recognized as a robust methodology for evaluating the environmental impacts of industrial products (Monteleone et al., 2024; Nortgate et al., 2007), its practical adoption within the foundry sector - particularly among SMEs - remains limited. Many SMEs

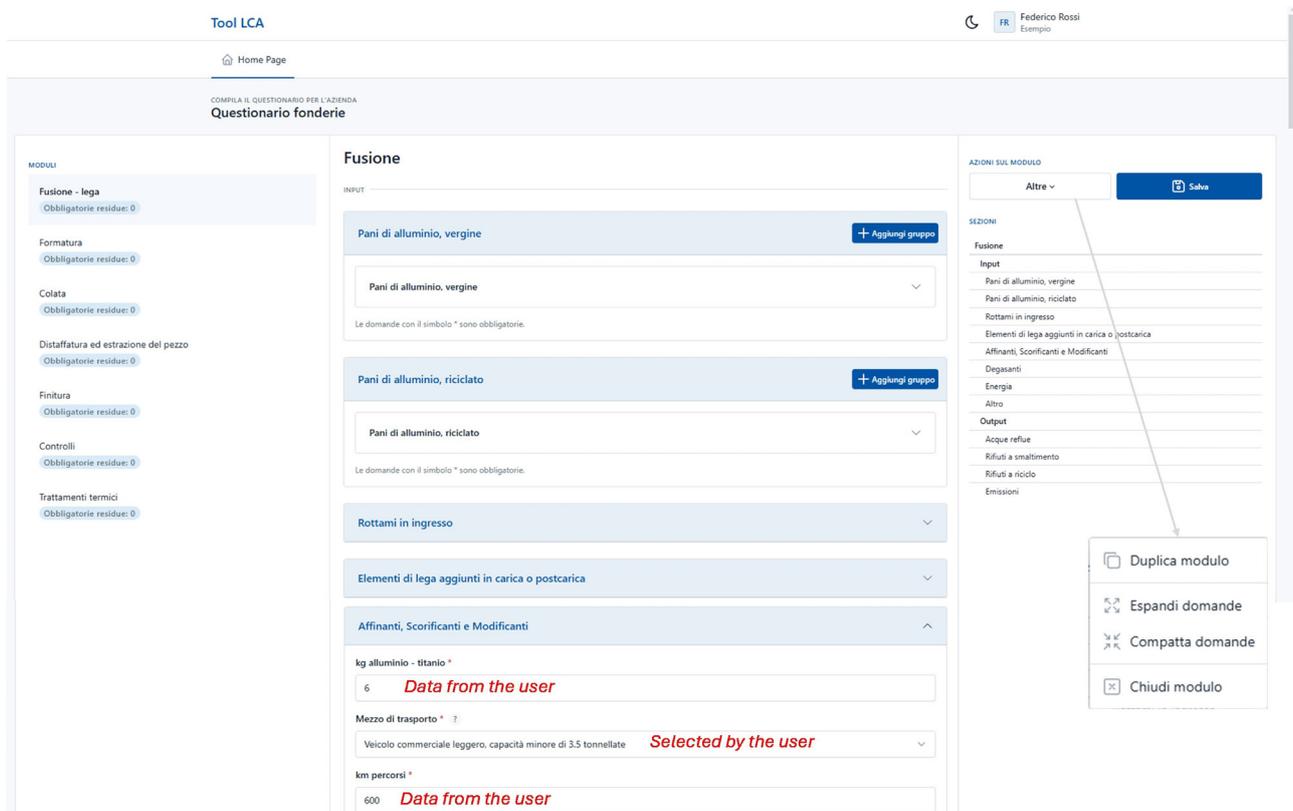


FIGURE 3: Main dashboard of the Eco-design tool.

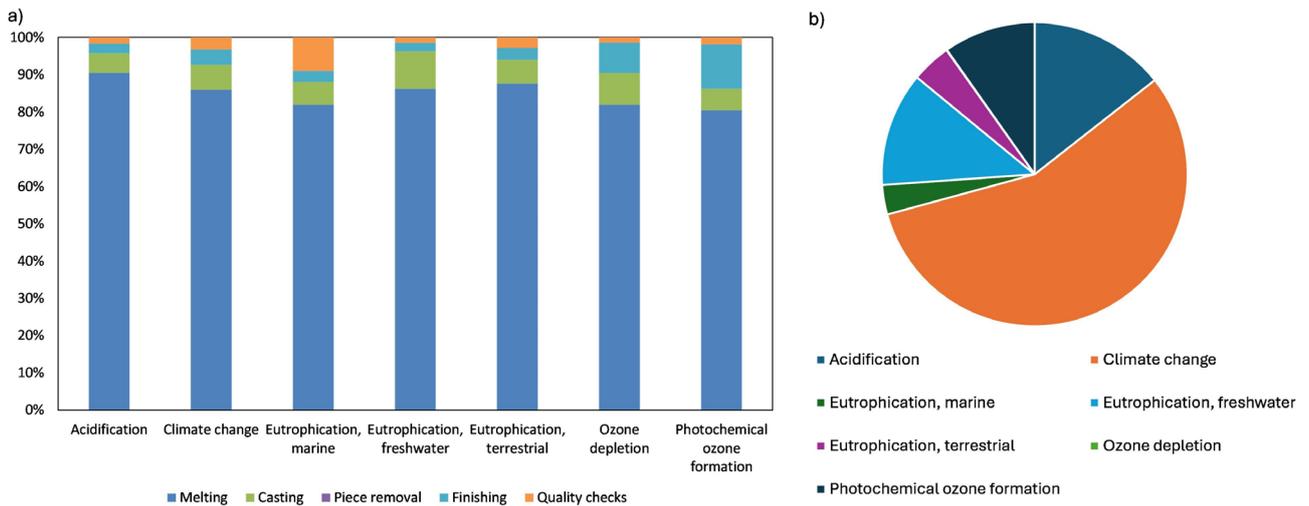


FIGURE 4: Results returned by the Eco-design tool.

face structural constraints such as a lack of trained personnel, insufficient access to specialized databases, and high costs associated with full LCA studies (Gómez-Garza et al., 2023; Ortiz et al., 2023). Nonetheless, these companies are increasingly asked by stakeholders - including clients and regulatory bodies - to disclose environmental performance data (Singh et al., 2021). Therefore, being able to monitor and improve their environmental footprint has become a strategic priority.

To bridge the gap between the complexity of traditional LCA approaches and the operational reality of SMEs, simplified tools are needed. As Gómez-Garza et al. (2023) argue, tailored methods are essential to support LCA uptake in resource-constrained contexts – such as the one of SMEs. In response to this need, the calculator developed in this study allows aluminum foundries to conduct a self-assessment of their environmental performance by entering site-specific data into a digital platform. This approach promotes a more agile and accessible form of environmental evaluation, supporting strategic decision-making and ultimately promoting wider participation in sustainability efforts and regulatory compliance.

This reinforces the crucial role of customized tools in overcoming traditional barriers to LCA adoption, paving the way for more inclusive and resilient sustainable development in the Italian aluminum sector. In fact, the customized calculator described in this paper aims to allow aluminum foundries not only to calculate their environmental performance, but also to do that in an agile and user-friendly way, inserting site-specific data on a digital platform that returns the eco-profile of their aluminum product (final or intermediate).

The developed tool has several practical implications, both for foundry managers and policymakers. In fact, while managers should cultivate a wider perspective, aligning their strategies with circular economy principles on a larger scale, policymakers can play key roles as both regulators and advocates for foundries, helping to create a supportive environment that enables their active participation in circular economy initiatives (Fellner et al., 2018).

From a managerial point of view, the calculator helps to develop an LCA of the aluminum product thus, allowing foundries to have critical data for external communication. Most of the Italian foundries belong to the supply chain of big companies which, under a normative point of view, need to collect data from the different actors of their supply chain. In this sense, foundries should be able to provide data as precise as possible (Feil et al., 2022). Moreover, LCA is crucial in supporting communication and marketing. Considered as a green marketing tool, besides a managerial one, LCA serves as the foundation for building a management strategy for emission reduction, which, if well communicated through appropriate indicators and Key Performance Indicators (KPIs), can evolve from being a purely technical tool to becoming a valuable element of strategic communication towards stakeholders.

An environmental assessment facilitates managers in the understanding of their production process, highlighting its strengths and weaknesses. Specifically, it could play a crucial role in identifying areas for improvement and establishing a strategy for continuous improvement. By providing a comprehensive assessment of environmental hotspots - such as energy consumption, emissions, and waste production - it enables managers to detect inefficiencies and prioritize actions for optimization (Finnveden et al., 2009). From a strategic perspective, the tool supports data-driven decision-making, allowing companies to set measurable sustainability goals, track progress over time, and adjust strategies accordingly. Moreover, by integrating eco-profile analysis into long-term planning, businesses can foster a culture of continuous improvement, enhance regulatory compliance, and strengthen their competitive advantage in an increasingly sustainability-focused market.

Ultimately, having a tool to calculate the eco-profile of a foundry can be highly beneficial for understanding its environmental performance, especially in the context of certifications like the MGI. The MGI is an environmental certification scheme promoted by the Italian Ministry of the Environment, based on the PEF methodology. It certifies the environmental performance of products made in

Italy, classifying them into three categories: A (better than the reference benchmark), B (in line with the reference benchmark), and C (worse than the benchmark; in this case, the logo is not granted). This classification is based on three threshold values based on a benchmark, which is the result of a sector-wide screening study conducted at the national level. Obtaining this certification requires companies to conduct a LCA of their products. However, if the assessment results place a product in Class C - indicating performance below the market benchmark - the company will not receive the certification. Conducting an LCA involves significant costs in terms of finances, expertise, and time, especially for small- or medium-size companies. Therefore, having the ability to self-evaluate a product's performance internally, without immediately commissioning an external LCA study, represents both an economic and strategic advantage (Singh et al., 2021). If a company finds that its product falls into Class C, it can implement an improvement plan and re-apply for certification once its environmental performance meets the required standards.

The tool also addresses a key issue in the Italian context: the lack of territorial representativeness in LCA studies available in the literature, which are often based on generic industry datasets (Brogaard et al., 2014; Liu and Müller, 2012). By enabling foundries to input localized, site-specific data, the calculator contributes to improving the accuracy and relevance of environmental assessments, which is crucial for ensuring reliable eco-profile evaluations (Rossi et al., 2025).

Last but not least, the developed tool could also be highly valuable for policymakers at the Italian level, particularly for defining PEFCR for aluminum foundries, building on the existing rules already developed for iron foundries under the MGI scheme. Since setting these rules requires data collection from foundries covering at least 51% of national production in terms of revenues - the threshold for representativeness in creating Product Category Rules

(PCR) - this tool can facilitate efficient and standardized data gathering across companies. Furthermore, the MGI scheme mandatorily requires that the proponents of PCR are at least 3 private companies, one of which shall be a small - or medium-size company. Encouraging broader participation through such a tool can support compliance with these procedural requirements. Achieving this level of representativeness requires coordination and data-sharing at scale. In this contest, the integration between the BRIEF and GRINS projects is strategic, as it leverages a broad network of participating companies.

A key barrier to overcome is to bridge the gap between the needs of industry and those of LCA practitioners. On one hand, LCA experts often lack access to primary data specifically collected for the geographical context under evaluation, which forces them to rely on industry-generic data in their analyses. On the other hand, foundries face barriers when advanced LCA modelling is required to assess the environmental impacts of their operations. As illustrated in Figure 5, the combined approach of the GRINS and BRIEF projects fosters mutual benefits: companies contribute data and, in return, receive simplified, tailored tools that enhance their capacity for self-assessment. At the same time, LCA experts are incentivized to support foundries in becoming more autonomous by providing tools adapted to their operational context. This collaborative model could help reach the data representativeness threshold required by MGI, laying the groundwork for the development of sector-specific PCRs for aluminum.

In our experience, the benefits of this virtuous cycle are evidenced by the increasing participation of foundries in the data collection campaign. Based on the data collected in GRINS, a first version of a calculator was developed within the BRIEF project. This tool has since been tested by some foundries that had not contributed with data during the GRINS data collection campaign. Two of them found the calculator poorly suited to their processes and are now

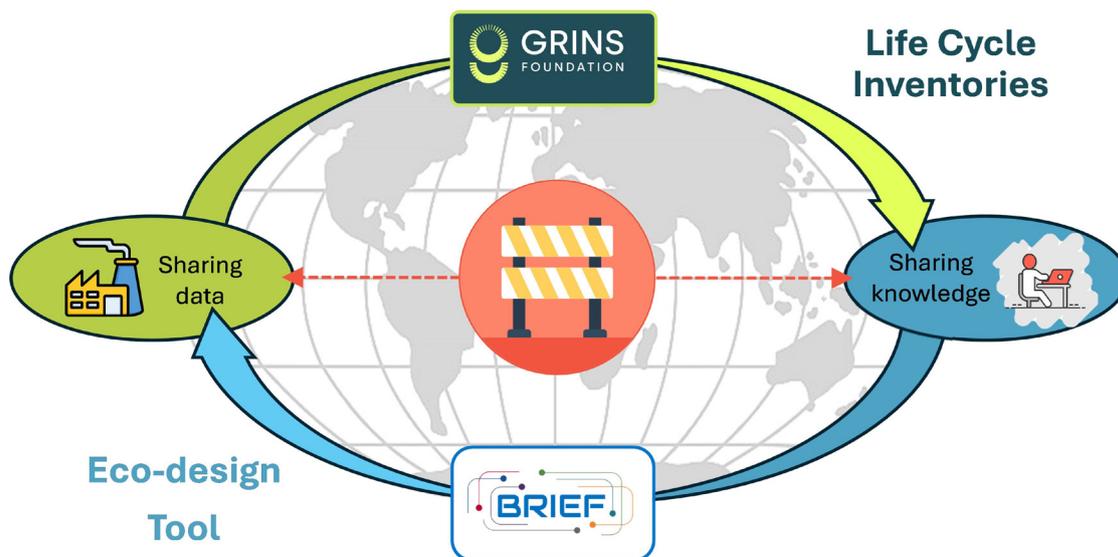


FIGURE 5: Sketch of the synergy between the projects GRINS (Growing Resilient, INclusive and Sustainable) and BRIEF (Biorobotics Research and Innovation Engineering Facilities).

considering providing data to better tailor the tool to their specific context. We believe that this synergy between foundries and LCA experts - currently involving a few dozen facilities - has the potential to grow exponentially as the calculator is adopted on a larger scale. This is essential to achieving the goal of defining PCR for MGI or other labeling schemes that require extensive representativeness at a certain geographical scale (e.g., national level).

However, the ways in which the data collection campaign will be extended is currently under definition. Moreover, by encouraging a widespread adoption of this tool among foundries, the ultimate goal is to drive the national industrial development towards decarbonization and broader green transition objectives, supporting a more sustainable and competitive Italian manufacturing sector.

4. CONCLUSIONS

The goal of this study was to present the development and application of a user-friendly Eco-Design tool aimed at supporting Italian aluminum foundries - particularly SMEs - in conducting a preliminary self-assessment of their environmental performance. The tool was designed to fill a gap in the availability of site-specific, accessible LCA-based instruments tailored to the operational context of smaller foundries, which often lack the capacity to perform full LCA studies. It provides indicative environmental profiles based on real production data, helping companies identify environmental hotspots and align with circular economy principles.

The tool has already been tested by 7 foundries, and feedback suggests it is perceived as useful and comprehensive by those that participated in the initial data collection. Nevertheless, the tool has some limitations. First, the accuracy of the results depends heavily on the quality and completeness of the input data provided by each company. Although the tool includes guidance for users, manual data entry can introduce inconsistencies. Furthermore, the current version of the calculator is based on data collected from only 15 foundries, meaning that results cannot yet be generalized to represent the entire Italian aluminum sector. However, the applicability of the software has significantly improved after implementing the feedback from the foundries. A practical demonstration of the results that could be returned by the software are presented in this manuscript, highlighting how they could be interpreted using an eco-design perspective.

From a practical standpoint, the tool offers an accessible entry point for companies wishing to understand and improve their environmental performance. It can support internal decision-making and external communication - especially for SMEs required to provide environmental information to larger clients or regulatory bodies. Moreover, the tool supports companies in evaluating their eligibility for environmental certifications such as MGI. In this sense, we believe that a synergy between the GRINS and BRIEF projects has a high potential, that is currently unexplored at large scale, to extend the platform of foundries in a virtuous cycle towards the achievement of a strong representativeness of the data collected on the Italian territory.

Future work will focus on expanding the user base and increasing the territorial representativeness of the data collected, with the goal of reaching the 51% production threshold required for the development of sectoral PCR under the MGI scheme. Further developments may also include refining the user interface based on user feedback and enhancing modularity to include additional production configurations. At the company level, future developments could include integrating the tool with enterprise management systems. By automating data collection, this integration would allow the tool to self-update with real-time information, reducing the burden of manual data entry and improving the reliability of results. This would not only streamline operations, but also make the tool a more effective resource for monitoring and improving environmental performance over time, therefore helping to bridge the gap between LCA theory and LCA practice.

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