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Assessing the Sustainability Impact of Improving Secondary Steel Production: Lessons Learned from an Italian Plant

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***Abstract* – This work presents a sustainability assessment approach to evaluate technological innovations in secondary steel production making use of Electric Arc Furnace (EAF) technology. The assessment covers the environmental, social, and economic dimensions of sustainability by combining different tools (Life Cycle Assessment and Analytic Hierarchy Process), and also provides an integrated assessment of the overall sustainability. The approach, which can also be used to support decision-making, has been applied to a real case study of a steel plant located in Northern Italy. In the case study, environmental sustainability is positively impacted mainly by increased metal yield and reduced furnace energy consumption. The greatest social sustainability benefits are mainly related to improved ergonomic and safety conditions for workers (reduced demand for physical effort, manual handling and repetitiveness, and lower risk of accidents), as a consequence of the introduction of Industry 4.0 technologies. Regarding economic sustainability, a positive impact related to reduced cycle time, increased metal yield and quality yield, reduced maintenance and quality control costs was observed. The integrated assessment of the overall sustainability has proven to be a viable approach to manage trade-offs between the different dimensions of sustainability.**

***Keywords* – Electric Arc Furnace (EAF); industry 4.0; Life Cycle Sustainability Assessment (LCSA); process industry; steel production.**

1. INTRODUCTION

Steel production plays a vital role in the global economy [1]. It is an energy-intensive industry and responsible for a large share of climate change emissions [2]. Indeed, according to the International Energy Agency, at global level this industry accounts for around 2.8 gigatonnes of CO_2 emissions per year, or 8 % of energy-related emissions [1]. As of today, companies operating in this sector face numerous challenges [1], [3]–[5]: rising energy prices, increased competition for raw materials, increasingly stringent environmental regulations, increasing global demand for steel, uncertain economic environment. To meet these challenges, technological innovations and management practices play a key role [2], [6], [7]. Currently, most of the innovations implemented by the steel industry aim to improve the

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sustainability of its operations. The most promising directions for this are artificial intelligence and other Industry 4.0 technologies, energy decarbonisation, supply chain integration, and strategic planning [8]. Since the steel industry is highly competitive and capital-intensive, investment decisions in technological innovations taken by companies are crucial for their long-term competitiveness, and mistakes made at this stage can jeopardise their very existence. For this reason, it is important that such decisions are supported by decision-making approaches able to take into account not only the classical financial metrics, but also the impacts in terms of environmental, social and economic sustainability. In the steel industry, the assessment of environmental sustainability as a decision support tool has long been widespread, especially using the Life Cycle Assessment (LCA) method [9]. However, the evaluation of the social impacts of technological innovations, and the integrated consideration of all the three dimensions of sustainability are far less practiced [10], [11]. This is in contrast to many other sectors, where overall sustainability assessments to support decision making are more widespread, such as in biopolymers [12], bioenergy [13], [14], energy policy [15], passenger transport [16] or mineral extraction [17].

In this paper, we present an approach for assessing the overall sustainability impact of technological innovations for process improvements in the steel industry. The approach was developed and tested in the context of a real case study set in a steel plant in Northern Italy.

The following sections provide a description of the research methods employed, including the sustainability assessment approach developed, and present and discuss the results.

2. Materials and Methods

The approach for assessing the sustainability of technological innovations in the steel industry was developed by the authors of this article. Its application was carried out in collaboration with the personnel of the company where the case study took place.

The case study company produces billets made of secondary steel, i.e. steel produced from scrap, using Electric Arc Furnace (EAF) technology. The production process consists of the steps shown in Fig. 1.

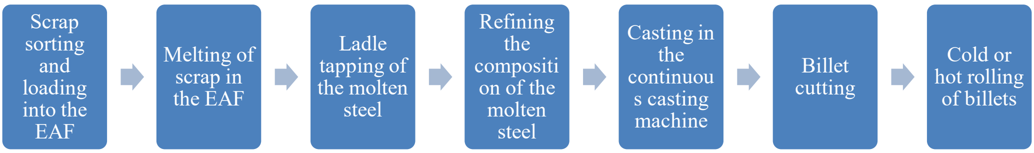

Fig. 1. Steps of the process for the production of secondary steel billets with EAF technology.

The sustainability assessment approach requires the comparison of two scenarios: a baseline scenario corresponding to the production process before introducing innovations and a scenario corresponding to the production process after introducing one or more innovations. The technological innovations implemented within the case study are listed in Table 1 and their impact was evaluated both individually and jointly.

The assessment approach uses different methods depending on the sustainability dimension under consideration. In particular, for environmental sustainability the approach adopts LCA as defined in [18]–[20]. This is a well-established method that, starting from an analysis of the mass and energy flows input and output from the different phases of a process, quantifies the resulting consequences for different environmental impact categories.

TABLE 1. TECHNOLOGICAL INNOVATIONS IMPLEMENTED IN THE CASE STUDY

ID	Process step/ Department	Description
1.1	Scrap sorting and loading	Scrap cleaning and charge mix optimisation: introduction of a machine that can magnetically separate metallic and non-metallic materials and use a charging algorithm to predict the yields of individual scrap classes. This machine also has a radioactivity detector to prevent the use of radioactive elements in the scrap.
1.2	Scrap sorting and loading	Automating the scrap sorting and loading phase: installation of a system to control the position of the loading cranes; definition of guidelines for the loading operator; installation of a vision camera and software for mapping the scrap pool and optimising the loading mix according to the steel grade to be produced.
2.1	Melting	Revamping of the chemicals injection system within EAF: installation of a set of furnace injection equipment with burners, oxygen lances, coal and lime injectors. Introduction of an algorithm-based system for dynamic process control in EAF in order to monitor the evolution of scrap melting, the agitation conditions of the metallic bath, and the interactions between steel and slag.
2.2	Ladle tapping	Eccentric Bottom Tap (EBT) automatic cleaning and reset system: implementation of an EBT status monitoring system with an automated duct cleaning and fast restoration equipment; introduction of an algorithm for ladle spill control and reheating management.
3.1	Continuous casting	New detaching agent deposition system in the ingot mould: implementation of a system to deploy an oil-powder emulsion as a detaching agent directly in the ingot mould, with the possibility of modulating the amount to be deployed according to actual need; use of an algorithm to take into account interactions between the solidifying skin, the ingot mould and the lubricant.
3.2	Continuous casting	Installation of a final electromagnetic stirrer: installation of an electromagnetic stirring system on the continuous casting line and implementation of a control system for the stirring system; an ad hoc implemented model enables the analysis of the nucleation of the solid phase, the morphology of the solidification microstructures and the distribution of the chemical segregating elements.
3.3	Continuous casting	Billet defect monitoring: implementation of a non-contact billet surface monitoring system (with a combination of optical, thermographic, and ultrasonic technology) and a data post-processing system to identify the presence of defects; a specifically developed algorithm makes it possible to identify the causes of defects and correlate them with process parameters.
4.1	Rolling	Defect analysis of rolled products: analysis of microstructure and grain size, evaluation of inclusion content and segregative state, characterisation of the main mechanical properties of rolled wire rod, analysis of defect types by metallurgical and statistical analysis.
4.2	Whole process	Development of new chemical product formulas: laboratory and plant tests; use of simulation software, microstructural characterisation and mechanical characterisation of products.
5.1	Whole process	Use of a 'MasterQuality' system for production supervision and tracking: implementation of a comprehensive and integrated production analysis system based on post-processing of large amounts of data and performance indicators.

With regard to the assessment of social sustainability, of economic sustainability, as well as of overall sustainability, the approach instead adopts the Analytic Hierarchy Process (AHP) [21]. AHP is one of the most well-known 'multi-criteria' decision-making methods. It is able to support decisions by prioritising different alternatives based on a set of attributes or criteria that may even conflict with each other, and it is founded on the principle of pairwise comparison between various alternatives. The sustainability assessment approach that we developed expresses the assessments in relative terms, rather than absolute terms. In particular, the sustainability is assessed in terms of whether, and to what extent, the innovations lead to an increase or to a decrease of sustainability with respect to the baseline scenario. This enables the use of AHP, a decision-making support tool, as a tool for evaluating sustainability benefits. In other words, the AHP enables the prioritisation of the innovative scenarios over the baseline one, based on the criterion of sustainability.

Moreover, the AHP is a particularly suitable method for assessing the various dimensions of sustainability, which by nature have a multi-factor character. For example, it allows for the use of qualitative estimates of certain costs affecting the economic sustainability, which may be difficult to quantify.

The application of the AHP was carried out by an assessment group made up of 7 people: 4 researchers (the authors of this paper), with expertise in the field of sustainability assessment, LCA and AHP, and 3 members of the company staff, hailing from operations and R&D departments, well-versed in steel production via EAF, with extensive expertise. The group met online several times to express the judgments required to the AHP. In particular, group judgements were made by means of a consensus vote on the pairwise comparisons and administered through voting. The group facilitator was the corresponding author of this paper.

The assessment group based its assessments and appraisals on qualitative and quantitative estimates and data related to the social and economic sustainability criteria described in Section 3. As envisioned by AHP, these judgments, which are subjective and qualitative, were subsequently translated numerically using semantic scales and processed mathematically in order to derive the results.

3. SUSTAINABILITY ASSESSMENT

3.1. Environmental Sustainability

To assess the environmental sustainability, we propose to use a comparative LCA, which could highlight the environmental impacts of the technological innovations introduced.

In the case study, the LCA covered only those scenarios related to innovations able to affect environmental performance. As a consequence, LCA has been applied to innovations ID 1.1, 1.2, 2.1, 2.2 and 3.2, for which we found an impact on environmentally relevant operational performance, i.e., metal yield, EAF power consumption, productivity and power on. The innovations considered were first evaluated individually and then jointly.

The system boundary was set as "cradle-to-gate": we included upstream processes, transportation, production processes, and utility services. On the contrary, we excluded the downstream production processes (e.g., rolling, subsequent treatment steps, and product use), since these processes were not affected by the implemented innovations, and therefore their environmental impacts were verified to be the same among the different scenarios. The functional unit was defined as 1 tonne of semi-finished steel product, which is C20D (0.21 % C) billet [22].

We collected primary data from the company (e.g., transport distances, metal yield, productivity, energy consumptions, and mix of primary energy sources to produce the consumed electricity), and secondary data from the *Ecoinvent v. 3.9* database (e.g., inventories for energy and transportation). We adopted ReCiPe 2016 as life cycle impact assessment method, as it is widely used and allows for the calculation of both midpoint and endpoint impact indicators, and *SimaPro* (version V9) software to perform calculations. More details on the LCA applied to the steel production process are available in a previously published paper [6].

3.2. Social Sustainability

For the social dimension of sustainability, we considered the levels of safety, health, ergonomics, and quality of working life of internal and external operators, both working in production and auxiliary services, such as maintenance.

In the evaluation, we compared the baseline scenario corresponding to the production process before the introduction of the technological innovations with different scenarios corresponding to the introduction of the technological innovations, both considered individually and jointly.

For this assessment, we adopted the AHP method. The implementation of the method took place through a series of meetings among the assessment group; during these meetings, we collected data and information on the potential impacts of the evaluated scenarios on the evaluation criteria and on the preferences of the company.

First, we defined the evaluation criteria. These criteria were structured in a hierarchy, i.e., an ideal structure that schematises and clarifies the decision-making problem and provides an immediate representation of the criteria related to the achievement of the objective and their relative contribution to the final decision. The objective, i.e., the assessment of social sustainability, is placed at the highest level of the hierarchy since it is the ultimate goal of the assessment process. The lower levels of the hierarchy show the criteria grouped by homogeneity in order to describe the problem with a progressive level of detail.

The evaluation criteria included in the hierarchy were defined on the basis of scientific and technical literature related to occupational health and safety, ergonomics and quality of working life [23]–[25]. The hierarchy is represented in Fig. 2.

Next, we carried out pairwise comparisons of the evaluation criteria (with respect to the higher criterion) and, with the help of the *SuperDecision* software (version 3.2.0) [26], we performed the necessary consistency checks of the answers and calculated the weights of all the criteria in the hierarchy.

In the next step, we made pairwise comparisons of the alternatives/scenarios with respect to each last-level criterion. In this case, it was not necessary to check the consistency of the answers since, having two alternatives under consideration (an evaluated scenario and the baseline scenario), consistency is inherently guaranteed.

We finally obtained the priorities (or preferability) of the alternatives/scenarios by means of matrix calculation.

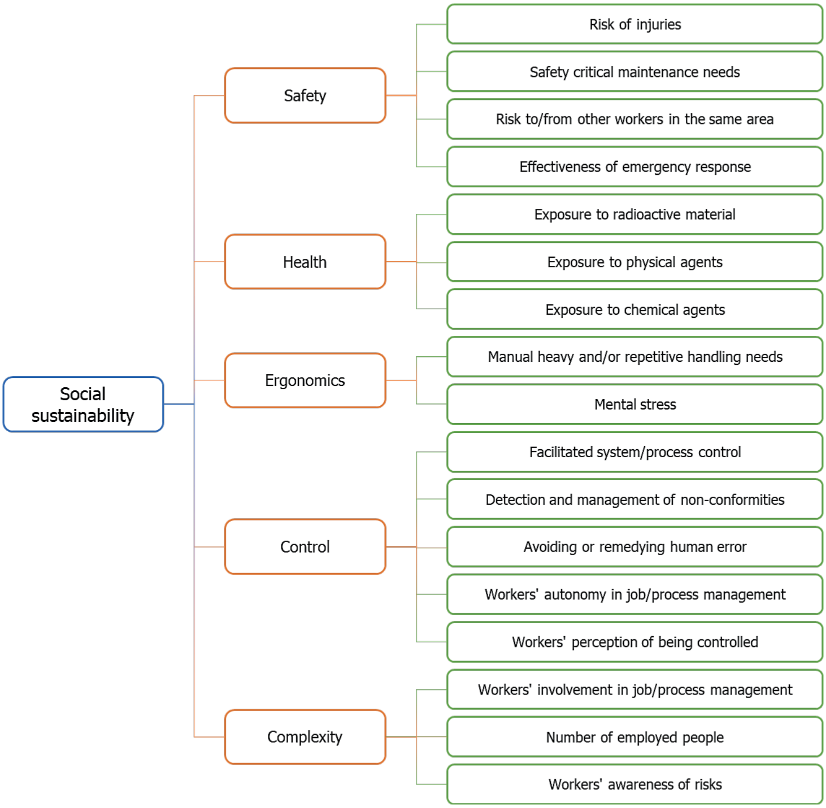

Fig. 2. Hierarchy for the assessment of social sustainability.

3.3. Economic Sustainability

We adopted the AHP method also for the economic sustainability assessment and comparatively assessed the impact of the introduced innovations. The steps followed are identical to those for the assessment of social sustainability.

In this case, the evaluation criteria included in the hierarchy were defined on the basis of the scientific and technical literature on the financial and non-financial performance of production systems (e.g. [18], [27], [28]). Fig. 3 shows the hierarchy of criteria adopted.

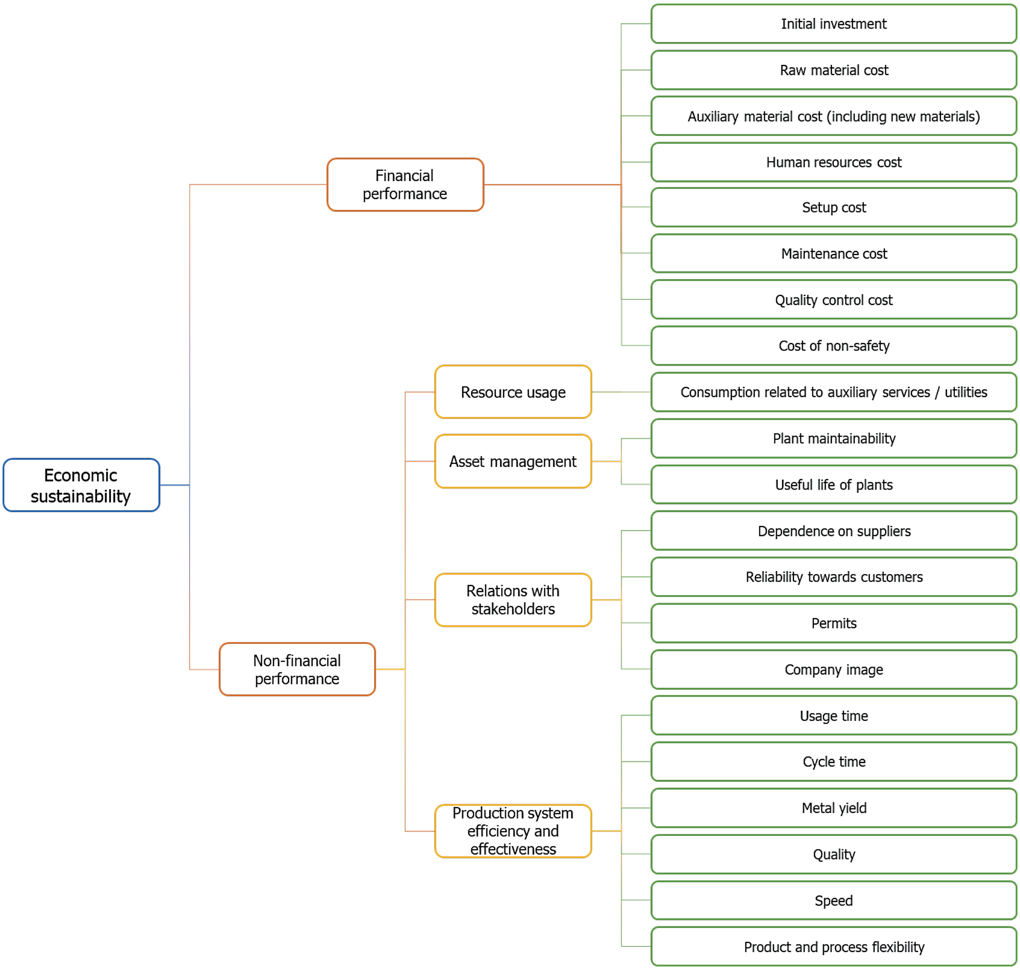

Fig. 3. Hierarchy for the assessment of the economic sustainability.

3.4. Overall Sustainability

In order to integrate the assessments made for the individual sustainability dimensions, the assessment approach again adopts the AHP method. In this case, the hierarchy of criteria consists of an objective, the overall sustainability, and one level of criteria: environmental sustainability, social sustainability and economic sustainability. The steps followed for the application of AHP are the same as in the two cases described above.

4. Results

4.1. Environmental Sustainability

As mentioned above, the assessment of the environmental sustainability has been extensively presented in a previously published article, that can be consulted for further details [6]. Table 2 summarises such results in terms of damage categories for the different scenarios analysed.

TABLE 2. VALUES OF THE ENDPOINT INDICATORS IN THE INVESTIGATED SCENARIOS

Damage category	**Scenario ID**					
	1.1	1.2	2.1	2.2	3.2	All
Human health (DALY)	–4E–5	–1E–5	–5E–5	–1E–5	–6E–6	–1E–4
Ecosystems (species.yr)	–9E–8	–3E–8	–1E–7	–3E–8	–1E–8	–3E–7
Resources (USD2013)	–2.44	–0.87	–3.26	–0.83	–0.39	–8.18

The negative results indicate that all scenarios lead to a reduction in damage for all three damage categories considered.

4.2. Social Sustainability

Table 3 shows the weights of the criteria within the hierarchy, and thus their relative importance for the assessment. These weights were processed by means of the matrix calculation described above. The weights are expressed as percentages.

TABLE 3. WEIGHTS OF THE CRITERIA (SOCIAL SUSTAINABILITY)

First-level criteria	**Weights**	**Second-level criteria**	**Weights**
Safety	25.47 %	Risk of injuries	10.43 %
		Safety critical maintenance needs	7.37 %
		Effectiveness of emergency response	5.21 %
		Risk to/from other workers in the same area	2.45 %
Health	25.47 %	Exposure to radioactive material	11.30 %
		Exposure to chemical agents	9.87 %
		Exposure to physical agents	4.31 %
Ergonomics	19.70 %	Manual heavy and/or repetitive handling needs	14.77 %
		Mental stress	4.92 %
Control	14.68 %	Detection and management of non-conformities	4.60 %
		Avoiding or remedying human error	4.60 %
		Facilitated system/process control	2.59 %
		Workers' autonomy in job/process management	1.45 %
		Workers' perception of being controlled	1.45 %
Complexity	14.68 %	Number of employed people	7.75 %
		Workers' involvement in job/process management	4.88 %
		Workers' awareness of risks	2.05 %

Table 5 shows the preferability of the scenarios expressed with respect to the baseline scenario and in percentages. These preferability values make it possible to assess whether an alternative/scenario is preferable to the baseline scenario from the point of view of social sustainability (values greater than 50 %) and the extent of this preferability, if any (the higher the value, the more preferable the alternative/scenario).

The preference values obtained show that all scenarios of interest, both those corresponding to individual technological innovations and the one representing the combination of all innovations, have a positive impact on social sustainability, since their score is greater than 50 %. Among them, the scenario considering all the innovations jointly is particularly preferable from a social perspective compared to the previous conditions (score of about 71 %). This scenario is more preferable than the baseline scenario for most criteria (12 out of 17), and it is equally preferable for the remaining criteria (5 out of 17). In particular, the improvement in social sustainability is related to the following aspects:

- Lower risk of accidents;
- Lower need for safety-critical maintenance activities for operators and maintenance personnel;
- Lower presence of potential interferences between operators or with external personnel;
- Lower possibility of exposure to radioactive materials;
- Reduced exposure to physical agents;
- Fewer handling or airborne chemicals;
- Reduced demand for physical effort, manual handling and repetitiveness;
- Easier control of the system/process by workers;
- Greater ability to detect and manage faults and defects;
- Increased possibility of avoiding or remedying human errors;
- Higher involvement of workers in process management;
- Higher number of employees.

Among the scenarios concerning individual innovations, those with the highest preferability are, in descending order: EBT automatic cleaning and reset system (2.2); new detaching agent deposition system (3.1); automation of the selection and loading of scrap (1.2). The innovations introduced increase the level of social sustainability mainly due to improved ergonomic and safety conditions for operators.

Considering all the scenarios assessed, the demands of physical exertion, manual handling and repetitiveness, the possibility of exposure to radioactive material, and the risk of accidents were the criteria with the highest weights. This result is a further confirmation of the relevance of ergonomics and safety criteria in the assessment of social sustainability.

Some criteria showed no preference between the baseline scenario and all other scenarios, and thus no differentiation. These criteria concerned: the effectiveness of emergency response, mental stress, workers' autonomy in job/process management, workers' perception of being controlled, workers' awareness of risks.

Finally, positive impacts for almost all technological innovations were observed with regard to the following criteria: detection and management of non-conformities, facilitated system/process control, the possibility of avoiding/remediating human errors, and the workers' involvement in job/process management. These positive impacts highlight the relevance of automation, modelling and simulation, and data management, which are all Industry 4.0 related innovations.

4.3. Economic Sustainability

Table 4 show the weights of the criteria for assessing economic sustainability, developed by means of the matrix calculation. The weights are expressed in percentages.

TABLE 4. WEIGHTS OF THE CRITERIA (ECONOMIC SUSTAINABILITY)

First-level criteria	Weights	Intermediate-level criteria	Weights	Last-level criteria	Weights
Financial performance	66.67 %	–	–	Initial investment	14.69 %
				Maintenance cost	11.04 %
				Quality control cost	11.04 %
				Raw material cost	5.98 %
				Auxiliary material cost (including new materials)	5.98 %
				Human resources cost	5.98 %
				Setup cost	5.98 %
				Cost of non-safety	5.98 %
Non-financial performance	33.33 %	Production system efficiency and effectiveness	13.14 %	Usage time	3.25 %
				Cycle time	3.25 %
				Metal yield	1.82 %
				Quality	1.82 %
				Speed	1.82 %
				Product and process flexibility	1.18 %
		Resource usage	9.82 %	Consumption related to auxiliary services / utilities	9.82 %
		Asset management	6.83 %	Plant maintainability	4.55 %
				Useful life of plants	2.28 %
		Relations with stakeholders	3.54 %	Dependence on suppliers	1.24 %
				Reliability towards customers	1.24 %
				Permits	0.67 %
				Company image	0.39 %

Table 5 shows the preferability of the alternatives/scenarios expressed with respect to the baseline scenario and in percentages. These preferability values make it possible to assess whether an innovation is preferable to the baseline scenario from the economic perspective (values greater than 50 per cent) and the extent of this preferability.

An analysis of the results shows that the combination of all innovations is preferable from the point of view of economic sustainability compared to the conditions prior to the introduction of the innovations (score of 66.92 %). The benefits are mainly in terms of reduced cycle time, increased metal yield and quality yield, reduced maintenance and quality control costs. Some innovations, taken individually, are less preferable than the baseline scenario from an economic point of view. In particular, these innovations are: scrap cleaning and charge mix optimisation (1.1); revamping of the chemicals injection system within EAF (2.1); new detaching agent deposition system (3.1); and installation of a final electromagnetic stirrer (3.2). This result is due, on the one hand, to the high ratio between initial investment cost and the magnitude of efficiency improvements and savings generated, and on the other hand to the weights of non-financial impacts, which in the application of the approach are lower than the weights of financial impacts.

4.4. Overall Sustainability

In the overall sustainability assessment, the weights given to the three sustainability dimensions using the AHP method are 41.7 % for economic sustainability, 32.7 % for environmental sustainability, and 25.6 % for social sustainability. Table 9 shows the preferability of the alternatives/scenarios compared to the baseline scenario and in percentages.

TABLE 5. PREFERABILITY WITH RESPECT TO THE BASELINE SCENARIO (OVERALL SUSTAINABILITY)

Scenarios	Preferability			
	Environmental sustainability	**Social sustainability**	**Economic sustainability**	**Overall sustainability**
1.1	66.62 %	56.30 %	49.32 %	56.76 %
1.2	55.14 %	60.40 %	50.81 %	54.68 %
2.1	70.47 %	55.71 %	48.25 %	57.43 %
2.2	55.06 %	65.32 %	51.91 %	56.37 %
3.1	50.00 %	61.54 %	48.82 %	52.46 %
3.2	52.34 %	52.01 %	46.87 %	49.97 %
3.3	50.00 %	52.78 %	50.31 %	50.84 %
4.1	50.00 %	52.78 %	50.77 %	51.03 %
4.2	50.00 %	58.16 %	50.31 %	52.22 %
5.1	50.00 %	52.35 %	61.77 %	55.51 %
All innovations combined	75.00 %	71.23 %	66.92 %	70.67 %

As we can see, the combination of all innovations is preferable from the point of view of overall sustainability. In addition, the innovations considered individually are also preferable to the baseline scenario, with the sole exception of the installation of the final electromagnetic stirrer (3.2), which is still very close to the 50 % threshold.

5. DISCUSSION AND CONCLUSIONS

In this work, we propose an approach for assessing the overall sustainability of technological innovations within the steel industry. The approach can also be used as a decision support tool and has been applied to a real case study set in a steel plant in Northern Italy.

It combines established methods such as LCA and AHP in a hybrid manner. This approach allows the evaluation to be based on a solid theoretical background and to rely on operational tools, such as software and databases for LCA and software for AHP, to facilitate its application in real contexts.

It is particularly suitable for assessing the impact in terms of overall sustainability of technological innovations in secondary steel production. Indeed, the evaluation criteria, in particular those contained in the two hierarchies for assessing social sustainability and economic sustainability, focus on the specific production process and working environment typical of companies operating in this sector. However, the approach can easily be adapted to all process industries, even outside the steel sector, with only the modification of some of the last-level evaluation criteria of the two hierarchies in order to more accurately represent the case under investigation.

The ability of the approach to integrate the judgements related to the different dimensions of sustainability into an overall judgement helps to take decisions for example in cases where an improvement in environmental or social sustainability occurs at the expense of economic sustainability.

As seen from the results, in the case study, the assessment was favourable to the technological innovations introduced for two of the three dimensions of sustainability and partially favourable for the third dimension. This made the final result, i.e. the assessment of overall sustainability, easy to achieve and essentially independent of the weights assigned to the three dimensions.

In general, the weights assigned to the three dimensions of sustainability are strongly influenced by the subjectivity and value system of the evaluator(s). When the assessment is made by a group of people, this can lead to disagreements and make it difficult to reach a shared outcome. This difficulty can be encountered despite the use of AHP, which, also thanks to pairwise comparisons, helps making assessments and taking decisions in an agreed manner. In such cases, it can be very useful to conduct a sensitivity analysis by calculating the ranges of variation of the weights of the three dimensions within which the overall preferability of an alternative does not increase (or decrease) beyond the 50 % threshold. This information is in fact of further support to evaluators or decision-makers. Moreover, the AHP allows this analysis to be carried out in a relatively straightforward manner and is therefore a suitable tool for the purpose.

Future work could involve expanding the stakeholder groups assessed for social sustainability, which is currently limited to workers. Additionally, to assess economic sustainability accurately, the assessment model should be reapplied once the implemented technological innovations have become regularised, enabling precise quantification of their impact on specific costs and on non-financial performance, which are currently only evaluated qualitatively.

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