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Linking Simulation-Based LCA to Manufacturing Decision Support: An Iron Foundry Case Study

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Abstract In recent years, an increasing number of legislations have mandated environmental impact evaluations of products from a life cycle perspective. This study applies a discrete-event simulation-based life cycle assessment to study the environmental consequences that respond to system configuration changes in production processes. The proposed method allows capturing the dynamic links in production processes, which is lacking in conventional static LCA modelling. This approach is demonstrated via a real-world case study of a Swedish foundry production line, where its environmental impacts' hotspots are identified. These environmental consequences are further analyzed to link to the respective production decision domains for providing suggestions on potential improvements. This study demonstrates the value of combining DES and LCA for revealing the hidden environmental consequences of production processes that are difficult to uncover with traditional LCA studies. Moreover, the strengths and difficulties of the proposed method are also discussed.

Keywords. Life cycle assessment, discrete-event simulation, decision making.

1. Introduction

The metallurgy industry has a significant environmental impact due to its high energy and materials demand [1]. Therefore, it is important to minimize the negative environmental consequences from intensive foundry activities. Life cycle assessment (LCA) is the most commonly used method to evaluate the potential environmental impact throughout a product's life cycle [2], and it is widely used in the product development phase [3]. However, its static nature limits its capability in assessing the environmental performance of dynamic characters in production processes [4]. On the other hand, simulation is a technique that imitates a real-world process over time. Its flexibility allows different future scenarios to be tested before implementation [5]. Several studies suggested to combine simulation and LCA, and taking advantage of them both [6]–[8]. The first incorporation of environmental consideration into simulation was introduced in 2000. In this study [9], a material flow simulation was performed using discrete event simulation (DES), and both economic and ecological factors were evaluated. Later, some studies used a similar approach but focused on assessing the energy consumption and the greenhouse gas emissions of different manufacturing systems [10]–[12]. After that, more studies indicated the limitations of the conventional LCA approach in manufacturing applications, and several different methods combining simulation models and LCA have been demonstrated [12]–[15].

2. Case study model build and data collection

The environmental impacts of foundry smelter are increasingly important as it is characterized by energy- and material-intensive processes [1]. Therefore, there is an interest in identifying parameters that contribute to potential environmental impacts for further optimization. This case study is performed on a Swedish foundry production line with the aim to identify the hotspots of its environmental impacts. The aim of the study is also to further analyze and link the environmental impacts to the respective production decision-making domains for providing potential improvements suggestions.

The case study follows the simulation-based life cycle assessment method proposed by [16], the steps of the method are illustrated in Figure 1. The method was developed in accordance with the ISO LCA framework [2] and Bank's [5] model for discrete-event simulation.

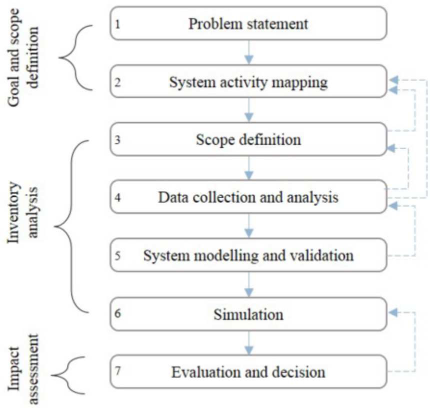

Figure 1. System analysis and modelling steps for simulation-based life cycle assessment.

2.1. Problem statement

In the problem statement, the purpose for carrying out the study and the intended audience needs to be defined. The aim of this case study is to find the possible environmental improvements of a chosen production line in the smelter. With an increased understanding of the parameters that contribute to environmental impacts, potential focus areas can be identified, and changes can be suggested. This goal is refined and broken down into the following sub-steps:

- Evaluate the environmental hotspots of the existing state of the production line.
- Link the environmental impact to the manufacturing decision-makers.
- Demonstrate how system configuration affects the environmental impacts.

2.2. System activities mapping

The system activities mapping is to understand the production processes, evaluate the environmental significance of all the activities, and ensure all critical parameters are considered in the scope. A conceptual model was built to facilitate identifying all possible activities and parameters that the simulation model requires. As shown in Figure

2, the conceptual model visualizes the smelter production processes, including energy and materials input and their accessioned emissions in the six sub-processes.

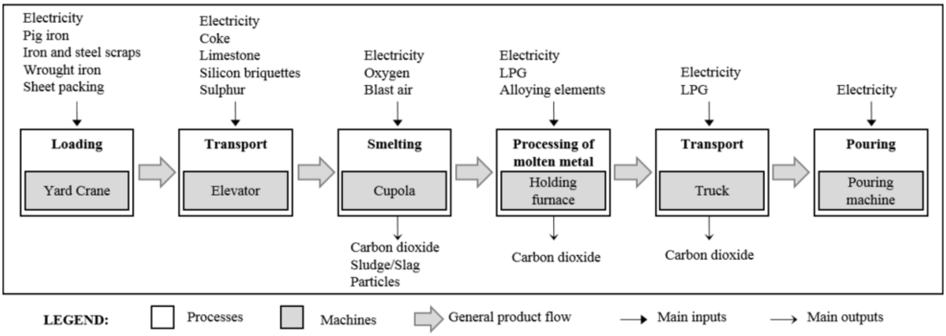

Figure 2. Conceptual model of the smelter with consideration of all the possible environment related processes and parameters.

A magnet crane transfers different amounts and types of iron and steel materials based on a basic recipe in the loading process. The recipe may vary depending on the materials' availability and the composition analysis results of the molten iron in the holding furnace. These various irons are lifted and moved with a crane and then dropped into a large container. The iron composite is then transported via elevator and conveyor into the copula furnace. The coke and different additives are also added to the iron mixture in this step. The smelting process takes place in the cupola, and the previous additives have different functions where some additives are burnt as fuel while others become a part of the final product. The majority (89%) of coke and limestone is combusted and contributes to direct carbon dioxide emissions, the remaining (11%), together with other additives, such as silicon, sulfur, etc., reacts with the iron and becomes a part of the final product. The processing time of the cupola furnace can be controlled based on several parameters, among which the amount of blast air and oxygen are two major influential factors. The molten iron is then poured into one of the two holding furnaces, depending on the availability. They serve as a reservoir for molten cast iron and are heated by liquefied petroleum gas (LPG) to a tapping temperature. Alloying elements are also added to the holding furnace to fulfill the mechanical and structural requirements before the melt reaches the pouring machine. In the next step, the molten iron is poured into a ladle and transported via electric-driven trucks. The LPG is used to keep the molten iron at a specific temperature. Finally, the molten iron is poured into the casting flask by the pouring machine.

While building the conceptual model, several parameters are considered to have a significant influence on environmental impact, as shown in Table 1.

Table 1. Possible environment-related parameters and activities for system activities mapping.

Production parameters	Environmental parameters
• Breaks and maintenances	• Iron mixture composition
• Capacity	• Coke, limestone, and additives consumption
• Availability	• Electricity consumption on different machine mode
• Mean time to repair	• LPG consumption
• Product variant	• Oxygen and blast air consumption
• Throughput	• Weight for product
• Process time	

2.3. Scope definition

In scope definition, the system boundaries and the functional unit are defined; moreover, the environmental impact indicators for the life cycle impact assessment are selected. A conventional cradle-to-grave LCA includes the raw material production, manufacturing, use, and end-of-life phase. In this case, the manufacturing decisions related to auxiliary material and energy use directly impact the manufacturing stage. In addition, through supplier selection, material, and energy source substitution, the environmental impacts from the previous stages are also affected. On the other hand, the environmental consequences in the succeeding stages, i.e., the use and end-of-life phase, are not directly affected by the manufacturing decision made in the smelter. Therefore, this case follows a cradle-to-gate LCA approach. To increase the manufacturing decision makers' awareness of LCA results, previous studies [17] proposed a method of defining the environmental performance of industrial actors' manufacturing systems, as shown in Figure 3. In their approach, only the environmental consequences related to energy use and material losses in processes under direct company control are included. The difference of their method compared to a conventional cradle-to-gate LCA is, that the environmental impacts from the production and use of the direct material, i.e., materials in the final product, are disregarded. In this case study, the environmental impacts associated with the iron mixture, additives, and part of the coke are disregarded.

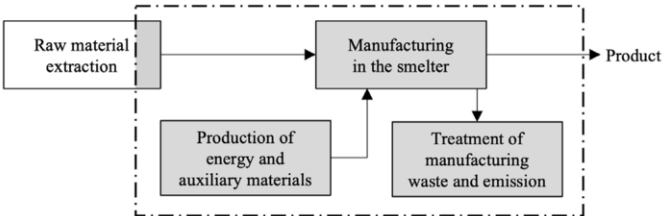

Figure 3. System boundary for industrial actor's manufacturing system.

In terms of the function unit, the production of 1000 kg molten iron is defined as the functional unit. The greenhouse gas (GHG) emissions, as well as the resource usage, are selected as the final impact assessment measures according to the case company's focus. To facilitate these measures, the following two impact categories from the CML method [18] are selected for the impact assessment:

- Global warming potential (GWP),
- Abiotic depletion potential (ADP, consists of ADP element and ADP fossil).

2.4. Data collection and analysis

Data is collected based on the parameters identified in Table 1, the following sub-session describes how the production and environmental data were collected.

2.4.1. Production data

Three data sources, interview, internal document (e.g., production logs), and direct measurement, were utilized for production data collection. The schedule for breaks and maintenances was obtained via the interview with the project manager. During breaks, the crane and all the transport are complete down. Maintenances are generally performed during the weekend with no manufacturing activities. The data regarding machine capacity, availability, and MTTR were gathered via interviews with process engineers. The different product variant, as well as throughput, was obtained from the internal production log. In terms of process time, the yard crane and elevator processing time were measured directly on-site and validated by the manufacturing operators. The processing time of copula furnace and holding furnaces were obtained via interviews with the process engineers, and one should note that the copula furnace's process time varies and is directly related to the melting rate. The melting rate is adjusted depending on the amount of molten iron in the holding furnace and the demand from subsequent processes. The processing time of the pouring machine was measured on-site.

2.4.2. Environmental data

The consumption data of coke, limestone, and different additives was collected from the production log. The oxygen and LPG consumption data were obtained from the purchasing record, which was the total consumption during a specific period. Data on electricity usage at the process-specific levels were obtained through direct on-site measurement by an electrician. The measurements were carried out during production, and two different machine modes: working and idling, were measured. During the maintenance period, the machines are entirely shut down; therefore, machines' electricity consumption is considered zero. The used Life cycle inventory (LCI) data in terms of material and energy production were obtained from the Gabi database [19].

2.5. System modeling and validation

After data collection, a discrete-event simulation model was built based on the conceptual model as shown in Figure 2. In the system verification, the critical activities and parameters are reviewed by production engineers to ensure that the simulation model correctly represents the behavior of the real-world system. In terms of model validation, the model's throughput was compared with historical production data with a minor deviation of 1.52%. In addition, the model's auxiliary material consumptions data were also compared to the historical data with a deviation of 1.92%.

3. Case study results

This chapter presents the main finding from the case study, the environmental hotspots of the production line are identified first, and then further analyzed and linked to the environmental impacts to the respective production-decision domains for providing potential improvements suggestions.

3.1. Environmental impact assessment

Figure 4 shows the contributions from different life cycle stages to the chosen impact categories. The impact from the raw material extraction phase is also included to provide an overview of the impact distribution. The impact from the manufacturing phase is divided into two parts: the impacts from the energy and auxiliary material production and the impact from their on-site usage. In GWP, emissions from the smelter contribute 64% of the total GWP impact, of which 92% comes from the combustion of the coke, and the rest is from the combustion of other energy carriers. The production of energy and auxiliary materials contributes 23% of the total GWP impact.

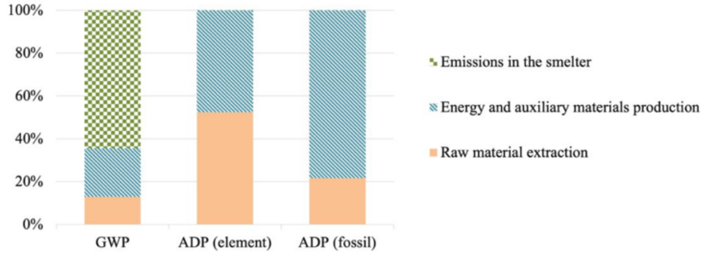

Figure 4. Conventional LCA approach: contribution of different life cycle stages to the selected impact categories.

In the ADP element category, the impacts from the raw material extraction and the energy and auxiliary materials productions are similar. Here, one should notice that the smelter used five different types of irons, in which only pig iron is the primary material and contributes to the abiotic depletion [18], the other four types of iron are all recycled materials, and their contributions to the assessed impact categories are negligible. Among all the assessed parameters, pig iron production contributes the highest impact, and the production of oxygen and electricity takes the second and third places due to the use of primary materials. In the ADP fossil category, 78% of the impact is from the production of energy and auxiliary materials, of which 85% of the impact is contributed by coke.

3.2. Linking the environmental impacts to manufacturing decision-makers

To support the decision makings from an environmental perspective, a decision support approach is suggested. As described in the scope definition, only the energy and material directly consumed in the company are included. In the decision support approach, impacts from different environment related parameters are classified and allocated to the different decision domains, which are defined by analyzing the roots-cause of the assessed parameters. Figure 5 shows a decision support approach, the assessed environment parameters are analyzed and classified into three summarized roots-cause decision domains: Blast air and oxygen, electricity, and other energy carriers used in production processes.

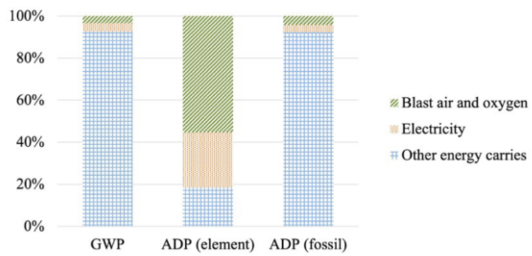

Figure 5. Decision support approach: contribution of different decision domains to the selected impact categories.

Compared to the conventional LCA application, the decision domain approach utilizes the same environmental impact categories for the final assessment but specifies and links more specific roots-causes targets for decision-makers with a systematic view of production process dynamics. Following are examples from the case study that demonstrate the benefits of the decision support approach.

Taking electricity usage as an example, in the decision support approach, impacts from electricity usage are separately extracted from the other energy carriers for decision-makers to consider from a life-cycle perspective. In the studied case, electricity usage impacts are more related to the system configuration, i.e., increasing the efficiency of the system will decrease the electricity consumption from non-value adding time. Whereas the other energy carries' impact reduction cannot be achieved by only adjusting the system configuration but rather finding alternative energy sources. The impacts from the oxygen and blast air consumption are complex and depend on several parameters; however, as the oxygen is regulated manually, the operator's experience is one of the biggest influential factors for oxygen consumption. The decision support approach provides a clear indication of impact contributions in each impact category. Results show that more than 80% of impacts to GWP and ADP fossil are coming from fossil fuel energy carriers and over half of the ADP element impact is contributed by the oxygen, providing clear working targets for decision-makers in reduction of any specific impact category.

3.3. Linking the environmental impacts to the system configurations

To support decision-making in the production process, system configuration is a key factor to be addressed for understanding how the system dynamics influence the environmental impacts. Figure 6 shows the machine utilization statistics of the case system. The figure indicates that the system is over-dimensioned in its production capacity as idling mode shares large percentages of the studied processes. Only the copula furnace process shows differently, this is however, not the bottleneck of the productivity, but rather due to the adjustable processing speed of the cupola is depends on the production demand of the molten iron.

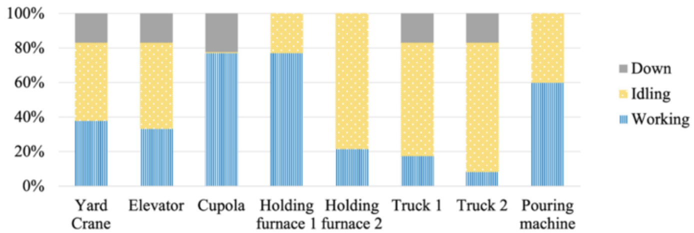

Figure 6. Machine utilization statistic.

To demonstrate how the production system configuration affects the environmental consequences, an alternative production scenario has been used by increasing the molten iron demand from the smelter. This was achieved by increasing 10% availability and reducing 25% takt-time of the subsequent line after the smelter.

Figure 7 compares the GWP impact of machine electricity consumption between the current and the alternative production scenarios. In total, a decrease of 28% of the GWP per functional unit is observed in the alternative scenario, and this is likely due to an efficiency increase in the smelter.

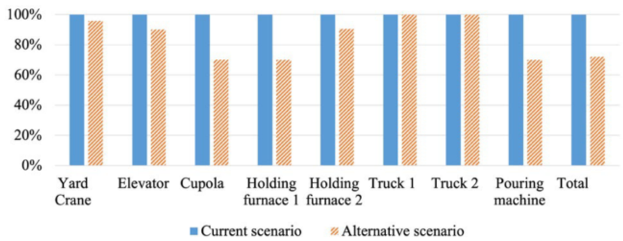

Figure 7. Comparison between current scenario and alternative scenario in GWP of electricity consumption.

Figure 8 shows the comparison of the normalized processing time distribution of the copula furnace, s1 is the lowest processing speed, whereas s4 is the highest. In the current scenario, the copula furnace runs at a lower processing speed. In the alternative scenario, the share of higher speed increases indicating the efficiency increases.

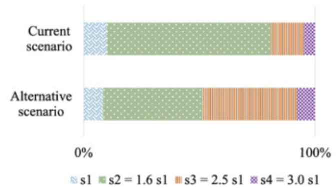

Figure 8. Distribution of processing speed of Copula furnace in different production scenario.

4. Discussion and conclusions

This study utilizes a method that combines life cycle assessment and discrete-event simulation to analyze the environmental consequences that respond to system configuration changes in production processes. The aim of the method is to support decision making in reducing the environmental impacts systematically. The benefit of the approach is demonstrated via a case study on a foundry and generated several considerations and limitations discussed as follows.

LCA requires extensive data collection to factifies accurate results. The simulation-based LCA approach can largely reduce the data management effort by utilizing the exiting production system model and facilities dynamic system results. Meanwhile, this method can be more beneficial when combining the decision support approach for dynamic results interpretation and extending the influence on the decisions as earlier as at the production development level, i.e., the substitution of the materials and energy carries. Additionally, separating different energy sources assessments in relation to system configuration will provide clear root causes related to each environmental hotspot. Nevertheless, this may have sub-optimization risk due to alternative energy source substation may lead to infrastructure change as well as total environmental consequences changes. To avoid such deficiency, a more sophisticated system model may be required to reveal the total impacts changes due to modification of the system infrastructure.

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