sustainability

MDPI

Article

Quick Green Scan: A Methodology for Improving Green Performance in Terms of Manufacturing Processes

Aldona Kluczek

Institute of Organization of Production Systems, Faculty of Production Engineering, Warsaw University of Technology, 86 Narbutta Street, 02-524 Warszawa, Poland; a.kluczek@wip.pw.edu.pl or aldona.kluczek@gmail.com

Academic Editors: Marc A. Rosen and Daniel A. Vallero
Received: 14 September 2016; Accepted: 30 December 2016; Published: 11 January 2017

Abstract: The heating sector has begun implementing technologies and practices to tackle the environmental and social–economic problems caused by their production process. The purpose of this paper is to develop a methodology, "the Quick-Green-Scan", that caters for the need of quick assessment decision-makers to improve green manufacturing performance in companies that produce heating devices. The study uses a structured approach that integrates Life Cycle Assessment-based indicators, framework and linguistic scales (fuzzy numbers) to evaluate the extent of greening of the enterprise. The evaluation criteria and indicators are closely related to the current state of technology, which can be improved. The proposed methodology has been created to answer the question whether a company acts on the opportunity to be green and whether these actions are contributing towards greening, maintaining the status quo or moving away from a green outcome. Results show that applying the proposed improvements in processes helps move the facility towards being a green enterprise. Moreover, the methodology, being particularly quick and simple, is a practical tool for benchmarking, not only in the heating industry, but also proves useful in providing comparisons for facility performance in other manufacturing sectors.

Keywords: quick green scan; green manufacturing; improving green performance; green company; green movement

1. Introduction

Green enterprises and their practices are becoming much more important in modern manufacturing.

Increasing requirements/pressure to comply with environmental regulations has compelled industrial enterprises and their manufacturing processes to operate in an environmentally friendly manner [1–3]. Several specific efforts are currently focused on enhancing manufacturing sustainability: the efficient consumption of resources, conserving energy, minimizing the environmental effects of energy production, and improving waste management systems [4]. Therefore, it is significant for production managers to analyze real-time production performance by tracking manufacturing equipment and technology [5]. The collected data allow the modernization or upgrade of their technology and even create opportunities for smart or intelligent manufacturing in order to improve the in-process quality and efficiency [2,5,6].

Environmental performance of industrial firms may be assessed based on green manufacturing and green products alongside waste management, recycling, the use of alternate sources of energy and compliance with environmental rules and regulations. Therefore, an overall evaluation of sustainable manufacturing processes for their harmfulness to the environment and society is needed to find relationships between environmental impact of their industrial activities, and the manufacturing processes which are of great importance. While researchers work to develop the "perfect" green assessment methodology, the manufacturers and practitioners do not have a quick and effective way to assess their industrial plants in order to start their journey towards green or more sustainable practices. Furthermore, in this context, production managers or decision-makers must also determine how they can improve the company's performance, identifying which objectives they can contribute to, within their area of influence. The improvement of production processes should be performed in the most suitable, effective way. The processes that show the highest potential for contributing to a company are dependent on the relevance of objectives formulated by company strategy in regards to green production systems, the improvement potential of each process itself and, in addition, small- and medium-sized enterprises (SMEs), which are often less able to afford dramatic changes and upgrades, must be shown how easily they can go green.

The concept of sustainable development requires industrial companies to adopt "green technology", which in many cases also improves a firm's profitability [7]. The challenge is to assess the firm's green impact, change existing manufacturing processes and determine the effectiveness of the changes in regards to the mission of becoming a green enterprise [8]. This endeavor requires the development of a toolset that can be applied at an enterprise level to perform an overall green performance assessment of manufacturing processes in a company producing heating devices. In addition, it will allow boiler manufacturers to optimize the production processes by reducing adverse environmental impacts.

Not many methods are currently available for quick, easy and effective assessment of company performance with regards to SMEs as a whole that also accommodates social concerns [9]. Therefore, an overall evaluation of sustainability manufacturing processes should take into consideration social objectives to find relationships between indicators describing the environmental impact of industrial activities and the manufacturing processes. The available tools for industrial plants' analysis of green performance are not sufficient enough in technological assessment. Furthermore, the tools do not estimate all the technical changes needed to bring sustainability issues into manufacturing processes. In this context, the production managers and decision-makers must determine how they can improve company performance by reducing pollution streams associated with production. Hence, there is the need to provide an appropriate tool to assess the degree of greening of the enterprise. As sustainability assessment principles, strategies and tools become more available, it is a challenge to integrate Life Cycle Assessment-based indicators, sustainability perspectives, along with linguistic scale into the manufacturing and logistic decisions to assess the degree of greening of the enterprise (or company sustainability) [10].

The purpose of this paper is to focus on assessing the green performance of the company in terms of manufacturing processes by developing a Quick-Green-Scan methodology. This is achieved by identifying green indicators, then applying improvements with technological changes within manufacturing processes, and evaluation of the company's performance. Bringing attention to greening enterprise is needed for several reasons:

- A more quick and integrated approach is needed for the improvement and green or sustainability assessment on the aggregated level against two scenarios: The sustainability should encompass economic, social, environmental and other relevant considerations.
- Referring to the previously mentioned point, the green assessment methodology must also be sufficiently generic and broad to cover as much of the detail as possible that would be covered in a comprehensive procedure. Moreover, this methodology must be usable in a straightforward manner by company decision-makers (users). The production process involves multiple sub-processes represented by various kinds of performance data. Various in-operations manufacturing technologies need to be based upon procedures for simplifying green or sustainability assessment in order to easily compare with the baseline scenario.
- The available assessment tools, such as Life Cycle Assessment (LCA) [11], Environmental Impact Assessment (EIA) [12,13], Cost Benefit Analysis (CBA) [14], Material Flow analysis (MFA) [15], social LCA [9] etc., require high-level expert competence.

- There is no unanimity yet as to which criteria and indicators or which method is better to use in green evaluation. In addition, there is a lack of a science-based methodology to describe specific manufacturing processes to generate inventory [16] data in a unified manner for whole manufacturing companies.
- The time devoted to performance evaluation is usually quite limited and the cost required to implement one of these later-mentioned tools is high,
- SMEs producing heating devices begin to consider technological changes (based on Best Available Technology) in manufacturing processes with respect to green measurements, since Best Available Technology (BAT) has been successfully implemented in terms of costs and benefits.

Despite all these early efforts, existing manufacturing paradigms are insufficient to meet requirements imposed by typical challenges and problems in the manufacturing. What is more, the estimation of environmental burdens and socioeconomic impact of manufacturing processes is very complex to accomplish since it is essentially processes-dependent. This means that when comparing existing manufacturing processes with their improvements, there is one peculiar aspect that has to be considered, which depends on the particular considered indicators within the criteria; the process can be somewhat the same in terms of indicators, operative parameters and so on to ensure comparable results. These problems are listed as follows:

- How to establish a methodology to evaluate an improvement of green manufacturing processes' performance based on the Life Cycle Assessment-based indicators framework and linguistic scale (fuzzy numbers) and to provide comparison of the performance for the baseline and improvement scenario?
- How to establish an overall Life Cycle Assessment-based indicators framework for manufacturing processes and integration with linguistic scale?
- How the proposed methodology can be applied to a company producing heating devices to assess and compare performances for both scenarios?
- By addressing the above challenges, a structured green scan (Q-G-S) methodology for assessing performance of manufacturing processes in a company producing heating devices is proposed. This methodology integrates a Life Cycle Assessment-based indicator framework as well as linguistic scale (fuzzy numbers) to evaluate the degree of company greening.

The objective of this paper is to assess and advance green manufacturing performance of the company producing heating devices through the implementation of more efficient, green improvements. The application of the suggested improvements to the manufacturing processes is illustrated through a case study. Improvement initiatives are expressed as technical solutions that are undertaken to achieve minimal waste and reduce hazardous emissions.

The Life Cycle Assessment-based indicators framework embodied in a linguistic scale (fuzzy numbers) is applied to analyze performance and then assess the degree of greening of the boilers' producer. However, the Q-G-S methodology for green manufacturing evaluation in the heating sector has not been examined in the literature.

The remainder of this paper is organized as follows. After a comprehensive review of the literature on the improvement of green performance in Section 2.1, Section 2.2 depicts an overview of key green tools and manufacturing indicators used to assess company performance. Then, a methodology to evaluate the improvement of green manufacturing processes' performance was elaborated in Sections 3.1 and 3.2. Section 3.3 uses a case study to show the process mapping, while Section 3.4 presents the setting of LCA-based indicators for green assessment. The suggested possible areas for improvement are shown in Section 3.5. Section 3.6 gives an application of the green assessment method in a boilers company. Finally, discussions and conclusions were given in Sections 4 and 5, respectively.

2. Theoretical Background

2.1. Need to Improve "Green" Performance

Today, environmental sensitivity calls for green—often interchanged with "sustainable"—practices [17]. The scope of green-business cases spans from product development to management of the entire product life cycle. These include eco-design, clean production, and reuse, with a focus on minimizing the expenses associated with manufacturing and distribution [18,19]. The concept of the firm's environmental performance image is well established in the academic literature and can take a wide variety of forms and manifestations by strengthening its green image [20].

"Green practice" refers to process-oriented environmental practices that use fewer resources, energy, or reduce the production of emissions and waste products. Therefore, "greening" requires enterprises to be open to transformation in terms of new production technology and to create a positive green image, which will be an unavoidable necessity for companies operating in environmentally sensitive industries where business activities have important social and negative environmental externalities [20]. Simultaneously, all these practices could improve an enterprise's environmental, economic and social performance [17].

The literature on environmental performance measurement and reporting is extensive. Some studies contain quantitative performance information as being brought on by increasing pressures from both government and competition on companies to make improvements to both their environmental and economic performance at the same time. Improvements to the manufacturing processes in terms of environmental performance have been undertaken by several studies [21–23]. Sarkis [24] as well as Rosen and Kishawy [4] took up these themes and examined the relationship between manufacturing and the environment, where profitability, productivity and environmental issues are increasingly viewed as strategic goals of enterprises. Empirical evidence supports a positive relationship between manufacturing and environmental impact [25,26]. To be green in production, enterprises should be involved in environmental and social responsibility as a starting point. This can be achieved by designing new production systems that use processes or technologies that are low or preferably nonpolluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers [27]. The need for this approach is particularly important in small- and medium-sized enterprises whose cumulative impact on the environment is often greater than that of large-scale initiatives. The green enterprise movement embraces much more than simply pollution-free manufacturing. It also includes pollution control equipment, and clean technology equipment of all kinds, as well as operating methods, such as waste management for minimal environmental impact [28]. Efforts are made to have lower energy consumption by using environmentally efficient materials. The energy requirements for production depend upon the requirements of advanced technologies as well as scale of machinery [11]. A good placement of facilities contributes to the overall efficiency of operations and can reduce as much as 50% of the total operating expenses, including energy savings [29]. All of these point to the importance of the environmental and economic aspects in manufacturing and make being a green enterprise an imperative. Much less attention in the academic literature—to the extent that the research about how industrial plants can improve their performance or through the utilization of green practices in terms of BAT technologies—is considered currently as a promising challenge for future research [20]. On the other hand, a firm's decision to initiate green production is influenced mainly by regulations and consumer preference [19,20]. Available literature covers the principles of green manufacturing, but there is little to no information on how these principles can be applied on an operational level [30]. Several studies have focused on "footprint" profile for quickly assessing sustainability or a green system model and their implication on specific industries [31]. However, they have not been employed on the process level [30].

As noted, the literature includes attempts to assess the sustainability of different manufacturing processes, based on the environmental impact of a common metric. Other literature is based on aggregated indicators under a single unit. On the other hand, the complexity of manufacturing processes may make green assessment impossible according to the various parameters. What is more, the data provided by companies is incomplete and not necessarily sufficient. Hence, there is need for providing decisions makers with an appropriate tool to assess a degree of greening of the enterprise.

Therefore, a green assessment methodology is needed to measure the environmental and socioeconomic performance of the enterprise to determine how these relations have evolved and can be explained. A new methodology—Quick Green Scan—will provide detailed guidance in terms of sustainable objectives on an approach for an overall, effective analysis of manufacturing practices as well as assistance with the identification and selection of improvement opportunities (scenarios).

Currently, there are no documented efforts of green enterprises in the boiler manufacturing sector in Poland. These enterprises do not incorporate a green approach in the overall aspects of manufacturing. The responsibility for environmental consequences of current industrial operations lies with those who are directly concerned with the production system. Manufacturers of heating appliances face a growing tension between customer demand, equipment cost, the need to maintain profit margins, and reputation for quality [32]. Lastly, the firms must make products that meet national and EU standards. All of these factors affect production. As a result, it is necessary to improve the company performance of manufacturing processes for SMEs producing central heating boilers in Poland.

This paper will introduce LCA-based indicators for manufacturing technology assessment, using which, the manufacturers can compare material, resources and energy consumptions, and assess the green impacts of improvement opportunities.

2.2. Tools and Key (Green or Sustainable) Manufacturing Indicators Used to Assess Company Performance

The act of manufacturing has a significant impact on the environment. This includes resource inputs, product life cycles and incidental wastes and emissions. Therefore, efforts have been made to analyze the manufacturing processes in terms of an environmental perspective. Analysis can be made using various approaches and tools to assess sustainability and environmental aspects within the manufacturing processes. Numerous tools which differ in their scope and approach focus on measuring disaggregated indicators in detail [33]. Fan et al. shortlisted a number of indicators used for sustainability manufacturing measurement and attempted to evaluate those based on the criteria of relevance [34], while Feng and Joung stressed the need to introduce the necessary tools and had the objective of determining the value of an indicator for a sequence of process units [35]. Tools are often based on an interdisciplinary approach to define how specific technologies might impact economic, environmental and social issues [33].

There are several existing "green/sustainable tools" that are or can be used to calculate environmental impacts and improve the environmental performance of an enterprise, or are available for assessing production processes. The most comprehensive of green instruments are Life Cycle Assessment (LCA) and Material Flow Cost Accounting (MFCA) or Life Cycle Costing (LCC) [36] or even life cycle sustainability assessment (LCSA) [37].

A formal, four-phase Life Cycle Analysis (LCA) is an approach that encompasses the environmental impact throughout product life cycle phases. The LCA identifies and quantifies energy and materials used and wastes released to the environment in the "inventory stages" as well as calculating, normalizing and weighing the impact of those inputs and outputs (in one or more categories) in the "assessment stage" of the method [16]. These impacts include human health and resources, and ecological consequences from "cradle to grave" [38]. The LCA, based on material flow, focuses on the identification and quantification of environmental loads, the potentiality of these loads and proposed environmental impact reduction [39]. However, some important limitations have been identified regarding the quality and availability of data and system boundaries which influences greatly on the applicability of LCA [40]. The problem of system boundaries and indirect effects in conventional, process-based LCA is addressed in the connection between LCA and input–output analysis [41].

Conventional LCA captures only those metrics that occur within the semi-arbitrarily-drawn system boundary (attributional vs. consequential life cycle assessment) [42]. Attributional LCA aims at describing the environmentally relevant physical flows to and from a life cycle. Consequential LCA aims at describing how the environmentally relevant flows from the technological system as a whole change in response to possible changes in the life cycle [43,44].

The combination of LCA and MFCA seeks continuous improvement of manufacturing processes [45]. In most cases, when an enterprise is intent on improving its sustainable performance, extended LCA + MFA + MFCA is used to assess the impact of manufacturing processes on the enterprise performance profile [46].

Thus, an integrated approach involves extended LCA and MFCA/LCC and provides a company-sustainability level analysis. This method takes into account the environmental impact in terms of resources, and cost and social criteria to be considered in order to identify the path toward sustainability and assess a company's overall green or sustainable performance level.

The development of LCA is "foreseen for the weighting step where the different impact categories and resources are compared and their relative importance quantified" [47]. On the other hand, as suggested for LCA by Schmidt and Sullivan [48], LCA is characterized by a lack of weighting. Avoidance of weighting implies equal weighting factors for the considered criteria. A hierarchy of criteria could be either quantitative or qualitative in nature, which are assessed by professionals or experts in the corresponding area. Unfortunately, many evaluation criteria are subjective and qualitative in nature [49]. This makes the task of expressing preferences using exact numerical values very difficult, hence, decision-making with a linguistic scale could reduce the bias of the expert's judgment and can be challenging in the evaluation of a facility performance [50]. Another method based on fuzzy set theory was used in an environmental impact assessment for evaluating the environmental impact of manufacturing processes, and even selecting processes when environmental impact is one of the factors to be considered [13]. That is why a detailed overview of the whole company can give an understanding of the current "greening" or sustainability of the company as well as identifying what kind of problems it is presently facing. In this case, a rapid green scan as an assessment tool will be useful.

Although in recent years, various methods and approaches have been developed for sustainability assessment at the national level or for cross-country comparisons, the issues of developing metrics for greening or sustainability in order to assess a company's performance at the process level is not properly addressed [51–53]. Most of the assessment tools are developed for a specific product rather than manufacturing processes, or parts of a manufacturing system [54]. Some part of them is focused on manufacturing environmental performance evaluation with indicators for product and process assessment [55–57]. Each method has its own uniqueness and accuracy due to the assumptions and information used. Apart from the advantages and comprehensiveness of the assessment methods, none addressed the overall aspects of environmental performance of manufacturing processes in the heating sector. Even though the combined LCA-based methods are noted in literature since the 1980s, no standardized indicators exist, but rather a range of different approaches. What is more, there is no agreement to apply these LCA-related indicators for covering the overall analysis of green companies in terms of manufacturing processes. Some of the most common publicly available sets of indicators for sustainability assessment are described in [54], where part of the tools address only environmental aspect, others focus on product assessment rather than manufacturing processes. Many social impacts can also be considered through economic assessment (e.g., employment). There are various quantitative and qualitative methods for evaluating social impacts (Refer to a review by Chhipi-Shrestha et al. [58]).

Indicators used by assessment tools can be difficult to analyze. However, they may avoid uncertainties due to normalization and weighting [54]. Tools, based on the environmental performance measurement, include the standard set of indicators applied to each manufacturing process as compared to most other tools which apply indicators to a specific case company (e.g., energy use) [31,59]. Standard indicators may not cover all aspects of specific manufacturing (e.g., hazardous substances, innovation). Only the indicator set used in the Measuring Environmental Performance of Industry report (MEPI) includes both generic and sector-specific indicators [59]. Generic indicators were applied across all sectors to capture environmental and business/management aspects of firms' performance [60]. Different classes of performance indicators have been proposed in the literature: environmental management; environmental achievements; prevention costs and environmental investment; operating environmental costs; physical indicators; compliance indicators [60].

However, environmental performance measurement in manufacturing processes needs to be seen in the wider context of the sustainable issue where several social indices are being considered across firms with the mix of indicators utilized by the tools.

There are also no relevant studies on approaches for quick, overall evaluation of the green performance in terms of manufacturing processes in the heating sector, taking into consideration social issues. However, the "green" evaluation methodologies of manufacturing technologies in this sector have rarely been examined in the literature.

The novelty of this research against related works is that it identifies and unifies indicators from the viewpoint of all manufacturing processes within one production and provides an overall basis for green performance evaluation in terms of manufacturing processes by applying the LCA indicators framework and fuzzy numbers. While the number of sustainability indicators in the literature is currently being used by various researchers, it is very hard to find the implementation of all the proposed indicators at the process level. Moreover, the focus of the available indicators frameworks has mostly remained at the product and organizational level. Additionally, there is no proper classification for the various processes, because they are characterized by different technical, often scattered parameters. This study tries to capture the realistic green parameters and also classifies them in a suitable process level, resulting in the improvement of green performance in terms of manufacturing processes.

Despite the significant achievements, the development of a structured Q-G-S methodology for green assessment within a context of manufacturing processes appears to be reasonable. Therefore, several topics have to be taken into account, some of them are:

- Specific improvements initiatives;
- The power of information technology;
- Determination of the possibility to measure green manufacturing performance based on LCA methodology and fuzzy numbers.

With the Quick-Green-Scan (QGS) methodology, it will be easier to compare the baseline and improvement scenario of manufacturing processes, as different processes use different sets of technical parameters for evaluating the greening.

Considering this research gap, this method is introduced to fill the gap in the assessment of homogeneous manufacturing processes with various functional units. To do so, it is necessary to be able to compare existing with improved processes by quantifying the environmental and economic effect in all relevant dimensions.

Additionally, there is a lack of holistic focus on green evaluation in SMEs. This illustrates the applicability of this research, where welding, cleaning, cleaning and painting processes are studied in a heating boiler manufacturing facility.

This paper presents a structured approach that integrates the Life Cycle Assessment-based indicators framework as well as the linguistic scale (fuzzy numbers) to assess the degree of greening of the enterprise. Thus, the intuitive nature of the methodology allows:

- the provision of a tool to easily assess the progress made at each manufacturing process, differentiating the improvements obtained due to sustainable outcomes from each workstation of the manufacturing process

Individuals who are not experts in the field of green manufacturing are able to make appropriate business decisions, taking into account environmental and social-economic facts or indicators.

3. Materials and Methods

The analysis and proposal for change are based on interviews, in-plant observation, and literature review. The methodology used depends on the complexity of technologies involved in processes, as well as the scope of the information available.

The company producing heating devices was chosen due to its high potential for technological changes, and its positive attitude toward green or environmental sustainability. The size and main activity of the enterprise are useful in specifying the ways in which they are likely to be affected or stimulated by the greening initiative.

3.1. The Methodological Approach

3.1.1. Definition of the Criteria and Indicators for Evaluation of Defined Scenarios

Indicators included in green evaluation should be reflected in the characteristics of the current state of technologies. These are indicators related to the possibility that technology implemented will improve a plant's performance.

Industrial plant operators need to identify relevant, coherent, accessible and representative indicators within the general industrial context in order to identify an overall green performance level. Therefore, the development of selection indicators should be based on the principle of LCA.

Instead of using a long, costly and time consuming method, eight indicators are designed and manufacturing technologies assessment can be assessed using two criteria grouped in two categories: environmental responsibility (E) and socioeconomic opportunity (SE).

A reasonable indicator set can be established based on adapted technological changes in an existing state of manufacturing technologies in the considered plant if the principles taken into consideration are as follows:

(1) Principle of life cycle assessment (LCA). The green or sustainable performance evaluation should consider the manufacturing life cycle of a boiler, including cutting, welding, cleaning, and painting. Therefore, the development of selection indicators should be based on the principle of LCA. Although in many investment decisions, social factors are often ignored by industry, the social impact is not separately assessed in this study, but economic factors, including labor safety and political stability, are among the factors that can be considered. Sustainability requires incorporating social and environmental objectives or constraints while undertaking this reconfiguration [4].

(2) Principle of "green technology" development or technology upgrading. Technology upgrading can be interpreted as the adoption of a greener technology helping a company to remain environmentally sound [6]. The selection of materials is also significant in reducing the environmental load. For example, recyclable components used to manufacture products enhance green performance. Materials with a high recoverability rate, which are safe, reliable and environmentally friendly, should be used. Efforts are made to lower the energy consumption through the use of energy-saving technologies and manufacturing techniques. The indicator framework should be constantly improved with the development and deployment of new technologies and equipment in the boiler sector over time. In addition, during the operation phase, sustainability objectives might change according to related domestic environmental laws and regulations, and governmental environmental policies. Thus, with advancements in manufacturing technologies or technology upgrading, relevant indicators are more likely to emerge/be introduced, representing a state of company performance. For criteria assigned in boiler production, BAT technologies were applied based on the studies of field research of the author [61].

(3) Principle of pollution prevention. The evaluation indicators system must protrude the idea of pollution prevention. It does not have to cover all the factors of environmental performance in boiler production. Nevertheless, it is necessary to take account of resource consumption (e.g., energy and steel, sand), environmental impact (e.g., dust, and scraps), socioeconomic impact (e.g., health and safety, production cost) in the production process. In this way, it would be possible to demonstrate that green or sustainable performance could be effectively evaluated through implementing the technology improvement scenario for boiler manufacture.

(4) The main goal of this paper is to establish a methodology to evaluate the sustainability level of manufacturing processes by identifying and defining indicators that contribute to the manufacturing process sustainability.

3.1.2. Establishment of Evaluation Scales

The scale used for assessing and improving company performance was defined based on the approaches depicted in [62–64]. Jolly proposed an approach that does not have a sufficient scale to be used for an evaluation of the environmental performance of an industrial company [62]. Hence, the scale was extended to use the linguistic scale and translate it into fuzzy numbers (refer to details by Zimmermann [65]). An environment-based decision is impossible to be clearly defined, especially in a situation where many processes differ from a technical point of view or they are characterized by different parameters. Due to expert's statements being uncertain in their nature, human thoughts are fuzzy and the problem being analyzed is complex. It is therefore proposed to apply fuzzy sets for the representation of linguistic scales. These facts cause linguistics scales to be appropriate for use in this case.

To evaluate whether the green manufacturing in the heating company has achieved the expected level of success (greening), three market indices with two criteria were defined as presented in Table 1 together with the evaluation scale. With the scenarios based on their objectives analysis, the manufacturing processes based on technology improvement can be evaluated. After linguistic evaluation of all criteria, fuzzy mean values are calculated separately for environmental responsibility criteria and external criteria. The next step is to defuzzify fuzzy means and to calculate the crisp mean evaluation of an internal set of criteria and separately for an external set of criteria. The author proposes to use a matrix approach for presentation and analysis of results, where external criteria with their environmental responsibility indicators are represented on one axis and internal criteria with their socioeconomic opportunity indicators on the other one.

Table 1. Initial linguistics scales for the evaluation of a set of indicators. Based on [62].

External Criterion: Environmental Responsibility	Low Value		←→	High Value	
E1. Non-energy efficiency (EE)	Very low	Low	Medium	High	Very high
E2. Material intensity	Very weak	Weak	Medium	Strong	Very strong
E3. Produced waste consumption/wastes generated and disposed	Very weak	Weak	Medium	Strong	Very strong
E4. Terrestrial acidification	Very negative	Negative	Neutral	Positive	Very positive
E5. Global Warming Potential (GWP)	Very negative	Negative	Neutral	Positive	Very positive
E6. Respiratory effects	Very poor	Poor	Medium	Favorable	Very favorable
Internal Criterion: Socioeconomic Opportunity	**Lowest Opportunity**		**←→**	**Highest Opportunity**	
SE1. Dynamic generation cost (DGC)	Very low	Low	Medium	High	Very high
SE2. Work environment footprint/Health and safety	Very negative	Negative	Neutral	Positive	Very positive
SE3. Environmental investment cost (average % of sales)	Very low	Low	Medium	High	Very high
SE4. Cost of protection of human health impairment	Very decreasing	Decreasing	Medium	Increasing	Very increasing

The scale was used to compare two evaluation crtiterion within two scenarios in manufactuing. For the "importance" criteria, the author used the following five linguistic terms to express the degree of importance: "Lowest value", "Low", "Medium", "High", "Highest value". The linguistics importance values expressed by the experts are fuzzified using trangular fuzzy numbers, which also fuzzify the linguistic preferences [66].

Table 2 presents the triangular fuzzy conversion scale. Triangular fuzzy number (TFN) is characterized by an ordered triplet of real numbers $<l_i, m_i, u_i>$. The lower l and upper u bound of fuzzy numbers depict the uncertain range that might determine the importance expressed by the experts's knowledge. m is the median value. There are three experts to evaluate indicators matrices for both scenarios. Aggregation operations on fuzzy numbers are operations by which several fuzzy numbers are combined to produce a single fuzzy number. In this study, the arthmetic mean is used to aggregate experts' fuzzy evaluations. The arthmetic mean aggregation operator defined on n triangular fuzzy numbers $<l_1, m_2, u_3>, \ldots, <l_i, m_i, u_i>, <l_n, m_n, u_n>$ produces the result $<l, m, u>$ where in Equation (1) [67]:

$$\bar{l} = \frac{1}{n}\sum_{1}^{n} l_i,\ \bar{m} = \frac{1}{n}\sum_{1}^{n} m_i,\ \bar{u} = \frac{1}{n}\sum_{1}^{n} u_i \quad (1)$$

Aggregated evaluation of environmental responsibility (E) and socioeconomic opportunity (E-S) is the mean of evaluations of lowest-level criteria (see Equation (1). Therefore, external and internal criteria are triangular fuzzy numbers. Both main criteria are evaluated using a scale from 0 to 1. Yager formula (see Equation (2)) is used for defuzzification (calculation of crisp value—w) [64]:

$$w = (l + 2m + u)/4 \quad (2)$$

If $l_i = m_i = u_i$, the fuzzy number gets a crisp number; the crisp numbers are fuzzified quoted by each expert by assuming fixed upper and lower limits.

Table 2. Fuzzy sets and initial linguistic scales (the triangular fuzzy conversion scale) [64].

Linguistic Scale	Very Low (VL)	Low (L)	Medium (M)	High (H)	Very High (VH)
Triangular fuzzy number (l_i; m_i; u_i)	(0; 0; 0.25)	(0; 0.25; 0.5)	(0.25; 0.5; 0.75)	(0.5; 0.75; 1)	(0.75; 1; 1)

3.2. Research Methodology

The aim of this chapter is to outline the research methodology used in the presented study to assess green manufacturing performance in heating boiler manufacturing. It introduces baseline and improvement scenarios to compare the performance of manufacturing processes using different sets of indicators for evaluating the greening. It determines which indicators have the largest impacts on greening and if processes are improved after upgrades.

The following steps are undertaken for green manufacturing performance assessment:

- Draw process mapping with the recognition of environmental problems that can be identified in the manufacturing processes. This step includes collecting and analyzing inventory data to establish the material flow diagram. This inventory analysis collects all data of manufacturing processes and relates it to the functional unit of the study, it examines the inputs and outputs (materials and energy consumed, produced waste) during the manufacturing processes from and to the environment.
- Establish a set of the LCA-based indicators for the evaluation of green performance in the context of manufacturing processes. The potential indicators are divided into two groups of criteria: internal and external. An internal criterion is represented by environmental responsibility performance. An external criterion is demonstrated by socioeconomic opportunity performance. Environmental responsibility performance indicators are useful to help the

company to decrease its overall environmental impacts. Socioeconomic indicators include cost of production, investment cost, healthy work environment, and social commitment. Indicators are particularly appropriate when manufacturing performance indicators to be analyzed and compared represent the outcomes of specific present and future improvement actions taken by the company.

- Establish evaluation scales for comparing and assessing company performance in terms of manufacturing processes. Initial linguistics scales for evaluation of a set of criteria shown in Table 2 are applied. Then, the scale is translated into fuzzy numbers.
- Assess green performance of existing manufacturing processes (baseline scenario) using the initial linguistics scales and their fuzzy numbers.
- Suggest possible areas for improvement in terms of technological changes in existing manufacturing processes. These improvements encompass technological solutions for mitigating pollution and their design characteristics, including the in-process, or in-plant modifications. This stage describes or analyzes the original state of equipment and pollution produced by the operations.
- Reassess green performance of the improved manufacturing processes as performed in step 4 (improvement scenario). By implementing green techniques and technologies from the perspective of environmental concern, green effects of proposed solutions are also presented.

The evaluation scheme presented in the study is illustrated in Figure 1.

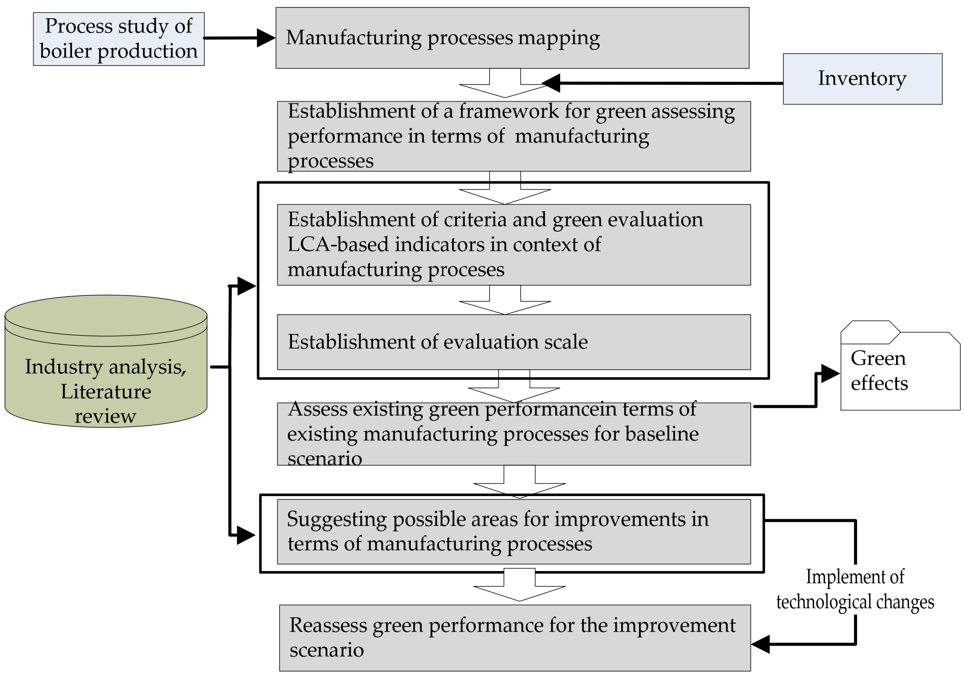

Figure 1. Green manufacturing performance evaluation scheme.

3.3. Process Mapping and Original State of Pollution in the Company

For pursuing a green enterprise, research starts with the recognition of environmental problems that can be identified in the manufacturing processes. The manufacturing of boilers has several sub-processes, including cutting, bending, welding, cleaning, painting, and final assembly.

All industrial processes involve the consumption and manipulation of energy and materials, and wastes and emissions [8]. These processes involved in manufacturing boilers generate large amounts of gaseous emissions and waste. These are mainly atmospheric emissions such as carbon monoxide (CO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), nitrogen protoxine (N_2O), sulphur dioxide (SO_2)

and dust from sand blasting, plasma cutting, and welding. These pollutants have negative impacts on air quality, human health and produce greenhouse gasses. These physical streams determine the relationship between an enterprise and the environment [59] as illustrated in Figure 2, which is important to examine when improving green performance in terms of manufacturing processes.

Data on input and output for baseline and improvement scenarios were driven from the company.

Inputs are represented by energy consumption and material consumption. Outputs are the amount of pollution emissions and waste generated.

Data on volatile organic emissions (VOCs) obtained from the company are summed. Energy consumption [kWh] was calculated using energy use per machine [kW], process specific data and operation time [h]. The times do not include changeovers, program changing and non-production activities.

Based on the inventory data for baseline and improvement scenarios (Table 3), evaluation of green performance is carried out for cutting, welding, cleaning, and painting. Bending and final assembly processes are not considered due to their low air pollution. Transport powered by internal combustion engines is not involved in the calculation.

The presented framework suggests that the path toward "greening" or sustainability necessarily requires a "green" evaluation methodology which can assess the level of greening of a company in terms of implementation of green technology for baseline and improvement scenarios. Table 4 includes evaluation objectives and example actions/measures that the company may adopt during performance evaluation. In evaluation of the performance, the evaluation should be against three status/options representing a certain level of impact (adverse; neutral; positive).

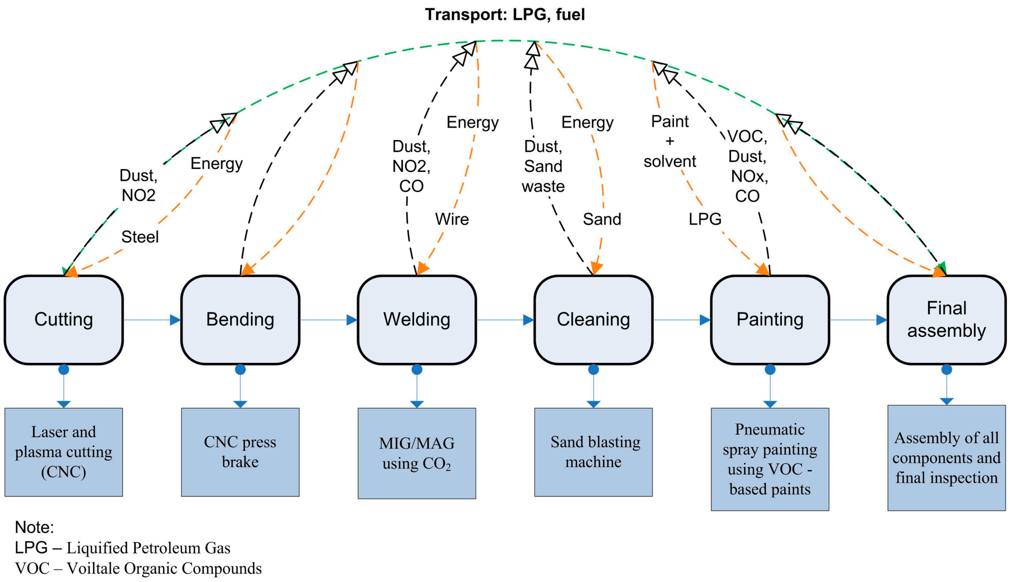

Figure 2. Environmental concerns associated with the process flow in boilers production for the baseline scenario.

Table 3. Baseline scenario vs. improvement scenario: Inventory data [61].

Existing Manufacturing Processes	T1	T2	T3	T4	Total	Improved Manufacturing Process	T1	T2	T3	T4	Total
Input						**Input**					
Steel	150,000	0	0	0	150,000	Steel	150,000	0	0	0	150,000
Sand [kg/year]	0	0	258,384	0	258,384	Shots [kg/year]	0	0	4200	0	4200
Electricity [kWh/year]	60,500	36,300	2,640 *	1,080	100,520	Electricity [kWh/year]	26,400	89,700	2200 *	47,520	165,820
Electricity [MJ/year]	217,800	130,680	9504 *	3888	361,872	Electricity [MJ/year]	95,040	322,920	7920 *	171,072	596,952
Fuel [MJ/year]	0	0	0	0	0	Fuel [MJ/year]	0	0	0	1,021,200	1,021,200
Paints [kg/year]	0	0	0	2500	2500	Paints [kg/year]	0	0	0	2500	2500
Solvent [kg/year]	0	0	0	502.00	502	Solvent [kg/year]	0	0	0	502.00	502
Welding wire [kg/year]	0	15,648	0	0	15,648	Welding wire [kg/year]	0	15,648	0	0	15,648
Output					**0**	**Output**					**0**
CO [kg/year]	0	62.6	0	7.2	69.8	CO [kg/year]	0	62.6	0	7.2	69.8
NO_2 [kg/year]	336	7.8	0	0	347	NO_2 [kg/year]	336	7.8	0	0	343.8
Dust [kg/year]	7.2	60.3	335	0	402.5	Dust [kg/year]	3.6	30.3	8.3	0	42.2
VOC [kg/year]	0	0	0	1465	1465	VOC [kg/year]	0	0	0	1465	1465
NO_x [kg/year]	0	0	0	54	54	NO_x	0	0	0	54	54
Waste						**Waste**					
Steel scrap [kg/year]	12,000	0	0	0	12,000	Steel scrap [kg/year]	9000	0	0	0	9000
Waste paint and varnish [kg/year]	0	0	0	350	350	Waste paint and varnish [kg/year]	0	0	0	350	350
Welding wastes [kg/year]	0	100	0	0	100	Welding wastes [kg/year]	0	100	0	0	100
Degreasing wastes [kg/year]	0	0	100	0	100	Degreasing wastes [kg/year]	0	0	100	0	100
Waste blasting material [kg/year]	0	0	258,384	0	258,384	Waste blasting material [kg/year]	0	0	4200	0	4200

* Not including electricity for compressors.

Table 4. A framework for green assessing of a manufacturing processes.

	Reducing Greening (Adverse Impacts)	**Neutral—Status Quo (Maintenance) or Mitigating Performance Impacts**	**Enhancing Sustainability—(Positive Impact)**
Objective (focusing on "attending green" "Attaining Suitability")	**Facilitating parameters of green manufacturing/Guiding assessment criteria (bold) and example actions/opportunities (dot points) for incorporation into company**		
Minimization of energy consumption	**Large increase in energy use in technologies with no measures**	**No significant increase in energy use, no change in manufacturing technologies in terms of energy use, minimization of energy consumption in production technologies**	**Reduction in energy consumption with measures taken to mitigate or reduce**
	• Establishes inefficient plant infrastructure which uses or contributes to the use of large amounts of energy over project life • No measures taken to incorporate energy efficient technologies	• Impacts limited to construction of production technology (i.e., energy-efficient technologies) • Management measures in place to manage e.g., use of plant/equipment that is electrically and/or fuel efficient • Maximize use of materials with low embodied energy	• Use of energy efficient production technologies (if reducing energy use over the status quo) • Plant layout and design that reduces the overall energy requirements

Table 4. *Cont.*

	Reducing Greening (Adverse Impacts) ⇦	Neutral—Status Quo (Maintenance) or Mitigating Performance Impacts	Enhancing Sustainability—(Positive Impact) ⇨
Minimization contribution to greenhouse gas emissions (GHG)	**Significant contribution to increased GHG emissions over life of project with no measures taken to mitigate or reduce**	**No change and/or minimizing project contribution to GHG emissions**	**Reductions in GHG emissions/changes**
	• No contribution to improve in-plant energy flow • No opportunities to reduce emission from electricity use	• No changes in energy flow and production using fuels to manufacture products • Impacts limited to production technology infrastructure • Contribution to reduce emission from electricity use on site	• Minimalize the burning of coal, natural gas, and oil for electricity as well as heat production at facilities for energy • Minimalize emission from electricity use on site
Minimization of air emissions	**Increase in air emissions and their impacts in local environment**	**No significant change or ongoing impact due to project and/or minimization of air emissions and impacts on a local scale**	**Reduction in air emissions and impacts on a local scale**
	• Increase in air emissions in manufacturing processes due to increasing production volume that results in air quality issues in the company and the local environment—no mitigation measures in place	• Short-term increase or generation of air emissions during manufacturing • Air emission control measures in place to manage (dust control, machinery maintained) • Contribute to minimization of air emissions by redevelopment of the existing production technology infrastructure	• Contributes to improved air quality (locally) • Development and implementation of environment management plan • Reduces existing air emissions from manufacturing processes • Reduces existing sources generating transport air emissions and improvements to transport flow • Air emission control measures implemented
Waste minimization and use of recycled materials; land contamination	**No control measures to minimize waste to landfill and/or incorporate recycled or recyclable materials and to the creation of land contamination**	**Control measures in place to manage waste and/or minimization of waste to landfill**	**Use of recyclable materials**
	• Waste reduction opportunities not investigated or opportunities to reduce or recycle waste not implemented • Introduction of potentially contaminating activities to previously not impacted areas with no treatment or management • Contaminants mobilized or spread as a result of works with no management	• Generation of waste avoided or minimized • Using materials for their future ability to be recycled • Minimizing material quantities where practicable • Use of production technologies requiring use of recycled materials • Existing site contamination remediated	• Using recycled content materials e.g., steel cut shots • Minimizing new building requirements and maximizing the reuse and redevelopment of exiting built infrastructure • Provisions to ensure waste or materials can be separated into reusable, recyclable and landfill to maximize reuse and diversion of suitable materials from landfill • Development of a waste management plan • Life cycle costing of materials • Contaminated material or sites appropriately managed to avoid impacts • No introduction of potentially contaminating activities to previously un-impacted/undisturbed areas without treatments in place

Table 4. *Cont.*

	Reducing Greening (Adverse Impacts)	**Neutral—Status Quo (Maintenance) or Mitigating Performance Impacts**	**Enhancing Sustainability—(Positive Impact)**
Minimization of social impacts of processes and production technology infrastructure	**No mechanisms to identify the opportunities, health impacts and social risks**	**Mechanisms to identify and mitigate the accidents potential social risks**	**Mechanisms to identify and mitigate the accidents and potential social risks, inc., adverse social impacts; significant changes in health and safety issues**
	• No opportunities to incorporate improvements for safety/access to hi-technology etc.—no employees contribution • No measurable health and safety interventions	• Project impacts offset through mitigation measures –noise barriers (not improvement) • Contribution to safety environment, industrial safety trainings	• Improved employee safety and security • Improvements in social and community benefits • Project will contribute to improved safety, reducing accidents • No measurable health and safety interventions
Practice of environmental guidelines/standards; maintenance practices including safety concerns waste disposal programs; availability of maintenance support in the form of tools and personnel	• Required environmental compliance • Waste treatment/disposal program or recycle waste not implemented • Unhealthy maintenance practices • Keeping the plant environment safe from environmental disaster • Meet legal regulations for compliance	• Commitment to enforce regulations/standards • Training and motivation • Management commitment in implementing the environmental standards, involving employees in policy making • Availability of skilled technicians • Availability of manufacturing support in the form of tools, spares and personnel • Communication that supports business objectives (reputation, brand recognition, etc.) • Meet legal regulations for compliance, with little voluntary activity	• Enhanced environmental compliance often exceeding minimal requirements • Auditing the impact of maintenance activities on environment and taking appropriate corrective actions • Implementation of ISO 14001 and ISO 50001 (environmental and energy management system, respectively) • Adequate training and motivation • Consistent communication on sustainable manufacturing practices; communication to support expanded business objectives • Implementation of the concepts of environmentally responsible manufacturing (ERM) • Developing green culture toward waste reduction during manufacturing and maintenance • Shift from simply meeting legal regulations for compliance to more voluntary activity, driven partly by market forces for sustainability objectives
Increase in economic operational efficiency	• Traditional economics	• Economic operational efficiency [2]	• Increased operational efficiency beyond that necessitated based solely on traditional economics [2]

3.4. Setting LCA-Based Indicators for Green Assessment

Possible metrics to be gained and overall impact of manufacturing processes on a whole company should be considered as shown in Table 5.

Table 5. LCA-based indicators used in the green evaluation.

Criterion: Environmental Responsibility	Major Contributors/Description
E1. Non-renewable energy	Total energy consumption [MJ/year]; Energy from different sources is considered: electricity, natural gas. Liquefied petroleum gas (LPG) for transport is included. Energy takes into account the energy demand per functional unit for the processes undergoing comparison.
E2. Material intensity	All form of material consumption expressed in kg per material cost in US dollars. In the study, material intensity includes restricted substances, especially important for cleaning or blasting (e.g., solvent, sand).
E3. Produced waste	Waste is considered as a useful quantitative indicator for measuring amounts that are finally disposed of at landfill. All wastes from production are both disposed and recycled [kg/year], e.g., waste blasting material.
E4. Terrestrial acidification	Acidification is caused by releases of protons in the terrestrial. In this study, the contributors to acidification were NO_2, NO_x, where acidification potential was calculated in SO_2 equivalents based on the appropriate conversion factors between different substances. SO_2 equivalence factors is 0.70 kg eq SO_2 [68]. Transportation of air emissions has not been included.
E5. Global Warming Potential (GWP)	The contributors to global warming were found to be CO_2, where GWP is calculated using Equation (3): $CO_2 = \Sigma$ (emission factor (kg/m^3 $\times$ GWP of GHGs)) $\times$ fuel (m^3)/1000, (3) CO_2 equivalent emissions are determined by multiplying the quantity of energy emitted by its GWP emissions relative to its source (for a time horizon of 100 years). Considered over a time span of 100 years, GWP values for these gases (CO_2, N_2O and CH_4) are 1; 310 and 21 respectively [68]. Thus, the propane (LPG) emission factors for the above-mentioned gases emitted to the atmosphere during the combustion of natural gas are 1530; 0.23; 0.03 (kg/m^3) respectively.
E6. Respiratory effects	Respiratory effects are caused by inorganic substances and CO. However, VOCs are the contributor to human toxicity. In this study, emissions, as the sum of VOC components, CO and dust (silica particles) have resulted in respiratory effects and are measured in kg into air.
Criterion: Socioeconomic Opportunity	**Major Contributors/Description**
SE1. Dynamic generation cost (DGC)	DGC shows what is the technical cost of obtaining an environmental effect unit (product), expressed in United States Dollars (USD) per unit of environmental effects. It is a ratio between discounted costs and discounted benefits. It is a dynamic index used widely in German banks and applied in Poland [69]. Additionally, the DGC indicator employs the Net Present Value (NPV) and Life Cycle Costing (LCC) expressed as all costs associated with the life cycle of boilers manufacturing [33]. Based on the data available in Tables 7 and 8, DGC may be calculated using (4): $$\int DGC = \frac{\sum_{t=0}^{t=n} \frac{KI_t + KE_t}{(1+i)^t}}{\sum_{t=0}^{t=n} \frac{EE_t}{(1+i)^t}}. \quad (4)$$ where: KI_t - investment expenditures in year t, KE_t - operational costs in year t, EE_t - an ecological effect in year t [assuming 4000 boilers through 20 year] i - a discount rate based on inflation rate, deposit interest rates and risk (18%) n - a lifetime of an investment (20 year). The value of DGC reflects technical costs of achieving one unit of effect in terms of the manufacturing process. Future costs and benefits (recurrent or one-time) are discounted to present values using Equation (5) [70]. $$NPV = \sum_{t=0}^{n} NFV\,(1+r)^{-t}, \quad (5)$$ where NPV is the present value of net economic cost, NFV is the net future costs, r is the real interest rate, and n is the total number of periods. Calculation of the NPV involves summing all the net cash flows associated with the proposed technologies throughout the economic life cycle, discounted before aggregation, in order to unify their monetary value [71].
SE2. Work environment footprint/Health and safety footprint	Absence from work due to accidents or work conditions; calculated as absence from work per worker in a given year divided by number of employees (90 persons).
SE3. Environmental investment cost (average % of sales) [%]	Investment costs describes the necessary monetary investment for new machines, tools or upgrading the existing ones. The investment also does not include the costs for equipment, coolant, and worker training.
SE4. Cost of protection of human health [USD/yearly]	Cost of protection of human health is expressed as the cost of avoiding air emissions (CO, NO_x, VOC, CO_2, dust) and waste disposed in the context of handling emissions within a particular quantity center

The cost estimate for the improvement of manufacturing processes is based on a survey of vendors and suppliers, and an interview with the company's operations management. Cost of capital includes the initial cost of the machinery, and installation. Based on the LCA-Based Indicators for Green Assessment placed in Table 5, current and improvement status of relevant LCA-based indicators was quantified for manufacturing processes as shown in Table 6.

Table 6. Current and improvement status of relevant LCA-based indicators.

	T1		T2		T3		T4	
Environmental Responsibility	***Baseline Scenario***	***Improvement Scenario***	***Baseline Scenario***	***Improvement Scenario***	***Baseline Scenario***	***Improvement Scenario***	***Baseline Scenario***	***Improvement Scenario***
E1.	217,800	95,040	130,680	322,920	9504	7920	3888	171,072
E2.	1.17	1.17	0.07	0.07	0.82	0.52	0.03	0.03
E3.	12,000	9000	100	100	358,384	4300	350	350
E4	235.2	235.2	5.46	5.46	0	0	37.8	37.8
E5.	38,720	16,896	23,232	57,408	1690	1408	691.20	30,477.8 *
E6.	7.2	3.6	122.9	92.5	335	8.3	1472.2	1472.2
Socioeconomic Opportunity	**T1**		**T2**		**T3**		**T4**	
SE1.	759.58	806.21	1304.41	1312.72	486.29	110.51	556.66	785.87
SE2.	0.03	0.02	0.03	0.01	0.01	0	0.06	0
SE3.	Cannot be determined	3.7 **	Cannot be determined	0.4 **	Cannot be determined	1.2 **	Cannot be determined	2 **
SE4.	56.96	60.41	21.94	32.07	4.14	32.07	2779.54	2776.86

* Sum of CO_2 eq emissions for electricity [30,413 kg] and fuel [64.80 kg]; ** Investment cost [KI_t] in USD for T1 = 322,580; T2 = 33,250, T3 = 105,450; T4 = 177,420.

3.5. Suggesting Possible Areas for Improvements in Terms of Manufacturing Processes and Their Green Concerns

The present study identifies activity areas that interfere with the environment and proposes a plan of objectives and actions to improve environmental performance. The latter can be achieved through adopting state of the art technological solutions and best practices and/or by the meaningful improvement of manufacturing processes directly located in the plant and substitution of the required material/energy flows. Technological solutions for improvements are related to capturing air pollution emissions from production.

Based on the findings and using the structured presentation of the relevant data in the company inventory, four areas for improvement were identified. The selection of technology to be implemented in the improvement scenario is also significant in reducing the environmental load, e.g., using materials with a high recoverability rate, which are safe, reliable and environmentally friendly. The analysis of green production implemented in a boiler company is summarized in Table 7.

Table 7. Analysis of green manufacturing implemented in a heating boilers company [72].

Manuf. Processes	Implement Green Techniques and Technologies	Current Situation and the Implemention Approaches of Green Manufacturing and Effects
T1	- The use of laser cutters - Workplaces converted to laser cutting will be equipped with filtered ventilation systems	*Current situation:* Sheets steel is cut using plasma by a computer controlled system which accurately produces the shapes designed in computer-aided design, computer-aided manufacturing system. *Green effects:* Workplaces converted from plasma to laser cutting machine with a separate ventilation system (filtering system) will reduce: - dust emissions from 7.2 kg/year to 3.6 kg/year - material waste—from about 12,000 kg/year down to about 9000 kg/year - annual reduction in electricity
T2	- The use of push–pull welding ventilation system with a high efficiency dust filter of 99% - The use of general ventilation with central vacuum and filtering systems equipped with cartridge filter units to reduce welding fumes and gases	*Current situation:* Cut steel sheets are bent using Computer Numerical Control (CNC) presses. The press is equipped with a laser sensing mechanism to guide the material during the bending process. *Green effects:* The installation of ventilation systems will reduce: - dust from the welding process up 30 kg/year - electricity and increased in electricity consumed by the ventilations systems is 192,240 MJ/year
T3	- Replacing sand blasting equipment and solvents degreasers with a shot-blasting booth with a closed abrasive circuit system, equipped with an integral filter system to reduce dust	*Current situation:* Welding of the boiler bodies with semiautomatic welders using the metal inert gas, metal active gas method (MIG/MAG) shielded with CO_2. A SpG3S-wire electrode is used as the welding material. Stations are equipped with jigs and fixtures, and lift points. *Green effects:* Install a dust-free, shot blasting booth with a closed circuit steel shot system: The shot blast booth will be equipped with an integral filter absorbing dust emissions. The new shot blasting installations will eliminate: - the need for 258 tons of sand by replacing it with steel shot for the cleaning abrasive (4.2 tons) - using steel shot blast instead of sand as the abrasive reduced dust emitted by the cleaning process by up to 8.3kg/year
T4	- Installation of the paint spraying and drying cabins with an air recirculation loop using hydrodynamic spraying as the application technique	*Current situation:* The process of applying paint is preceded by thorough cleaning of the boiler bodies: sandblasting, scrubbing, wiping, and sometimes degreasing. The solvent-based paint is applied pneumatically. Pneumatic spray painting uses compressed air, dispersing the coating material. *Green effects:* Ventilation systems installed in these booths capture up to 1465 kg/year of VOC rich emissions. Installation of paint spraying and drying booths requires more electricity (46,440 MJ/year) for paint application from the base scenario (1080 MJ/year).

Based on Equation (4), elements of DGC were calculated as presented in Table 8. Table 8 shows the operational cost matrix by type of manufacturing process and its cost. Material, energy, labor, emission and waste costs were calculated in the following way [46]:

- Material costs: costs are determined by multiplying the amount of the particular materials by their specific prices and summing up the results;
- Labor costs: labor costs are calculated in the man-hours required by each machine: labor cost per year is multiplied by (1 + f)/average hours per year, where f is a social cost of labor;
- Energy costs: electricity and fuel costs are included in the calculation. The energy consumption of each examined process is allocated to each quantity center by machine-hour. Energy is often subsumed under the term of material. The energy costs are treated as part of the material costs;
- Waste management costs: waste costs are all expenses which occur in the context of handling waste losses within a particular quantity center;
- Emission cost: emissions (CO, NO_2, dust, VOC, NO_x) are calculated similar to the waste.

Table 8. Elements of DGC calculation included in green manufacturing performance evaluation assuming a production volume of 1000 tons and manufacturing time of 1000 h for T1, T2, T3 and 800 h for T4 [46].

Process/ Operational Cost	Electricity	Fuel	Materials	Labor	Waste	Emission	Total Production Cost [KE_t]
Improvement scenario							
T1	5016	0	128,500	4687.50	−2340	56.96	138,203.50
T2	18,747.30	8932	212,966.40	7812.50	100	21.94	248,458.20
T3	1672	0	8106	6250	15.71	4,14	16,028.00
T4	9028	32,000	93,962.60	6250	29	2779.54	141,240.60
Baseline scenario							
T1′	11,495	0	128,500	4687.5	−3120	60.41	144,682.50
T2′	6897	8932	212,966.4	7812.5	100	32.07	236,872.03
T3′	6897	8932	212,966.40	7812.50	100	32.07	92,626.6
T4′	205.20	0	93,962.60	6250	29	2776.86	106,029.52

3.6. *Assess Green Performance of Existing and Improvement Manufacturing Processes*

Table 9 depicts a collection of expert valuations of manufacturing processes in the analyzed company. Linguistic scales and applied fuzzy sets are described in Section 2.2 (Tables 1 and 2). Fuzzy means are calculated as means of fuzzy sets corresponding to oral values assigned by three experts to specific indicators within the criteria. For example, linguistic evaluations of criteria (environmental responsibility for the indicator E1 (Non-renewable energy) and corresponding fuzzy sets are M and (0.25; 0.5; 0.75); H and (0.5; 0.75; 1); M and (0.25; 0.5; 0.75). Therefore, l-value of the fuzzy mean is an arithmetic mean of l-values for indicators E1–E6. Analogically, m and u-values of the fuzzy mean are calculated. The results of calculation are presented in Table 9.

The two scenarios were compared with respect to all the indicators within two criteria (Table 9). By using the geometric mean for each indicator of fuzzy matrix, separately for environmental responsibility and socioeconomic opportunity, Table 9 can be obtained. Crisp values w obtained with Yager formula (l + 2m + u)/4) of defuzzification are 0.51 and 0.50 vs. the improvement scenario with 0.729 and 0.625, so company performance is placed in the top right part of the manufacturing processes portfolio matrix.

Mean values of triangular fuzzy sets calculated for environmental responsibility are (0.25; 0.524; 0.708) and (0.313; 0.50; 0.686) and socioeconomic opportunity with values (0.417; 0.792; 0.917) and (0.25; 0.688; 0.875).

Figure 3 presents an interpretation of green performance evaluation for the analyzed company. Three zones of the Pfeiffer's portfolio matrixes are made, represented by green, yellow, and red colors [73]. The maintenance zone of the matrix in yellow color informs about neutral green performance evaluation. Decision-makers should consider retaking the assessment after the implementation of suggested improvements and observe the performance to analyze if it moves in the direction of the green zone. Further analysis should be conducted.

Table 9. Evaluation of green manufacturing performance: (**a**) for the baseline scenario; (**b**) for the improvement scenario.

		Baseline Scenario (a)		Improvement Scenario (b)	
		Linguistic Scale	TFN	Linguistic Scale	TFN
Environmental responsibility	E1	(M; H, M)	(0.25; 0.75; 0.75)	(M; L; M)	(0.25; 0.75; 0.75)
	E2	(H; M; H)	(0.5; 0.5; 1)	(H; H; H)	(0.5; 0.75; 1)
	E3	(M; M; M)	(0.25; 0.5; 0.75)	(M; VH; M) M)	(0.25; 1; 0.75)
	E4	(H; VH; VH)	(0.5; 1; 1)	(H; VH; VH)	(0.5; 1; 1)
	E5	(NL; M; L)	(0; 0.5; 0.5)	(M; H; H)	(0.25; 0.75; 1)
	E6	(L; NL; NL)	(0; 0; 0.25)	(VH; VH; VH)	(0.75; 1; 1)
Socioeconomic opportunity	SE1	(VH; H; H)	(0.75; 0.75; 1)	(M; H; M)	(0.25; 0.75; 0.75)
	SE2	(NL; NL; NL)	(0; 0; 0.25)	(VH; VH; VH)	(0.25; 0.5; 0.75)
	SE3	(L; L; L)	(0; 0.25; 0.5)	(M; H; H)	(0.25; 0.75;1)
	SE4	(H; VH; H)	(0.5; 1; 1)	(M; H; H)	(0.25; 0.75; 1)
Fuzzy mean evaluation (l_i; m_i; u_i)	E1–E6		(0.25; 0.542; 0.708)		(0.417; 0.792; 0.917)
	SE1–SE4		(0.313; 0.50; 0.688)		(0.25; 0.688; 0.875)
Crisp value w			(0.510; 0.500)		(0.729; 0.625)

Negative results represented by the dead zone in red inform that the company does not become green. This zone has no perspective to become greener. The company does not see the need for actions because it does not understand the environmental hazards and green effects or know what it can do to help.

Positive result—the green zone in a green-company does become green, creating an image of environmental and social responsibility and appealing to environmentally conscious consumer producers. A company going green improves the overall efficiency of its performance.

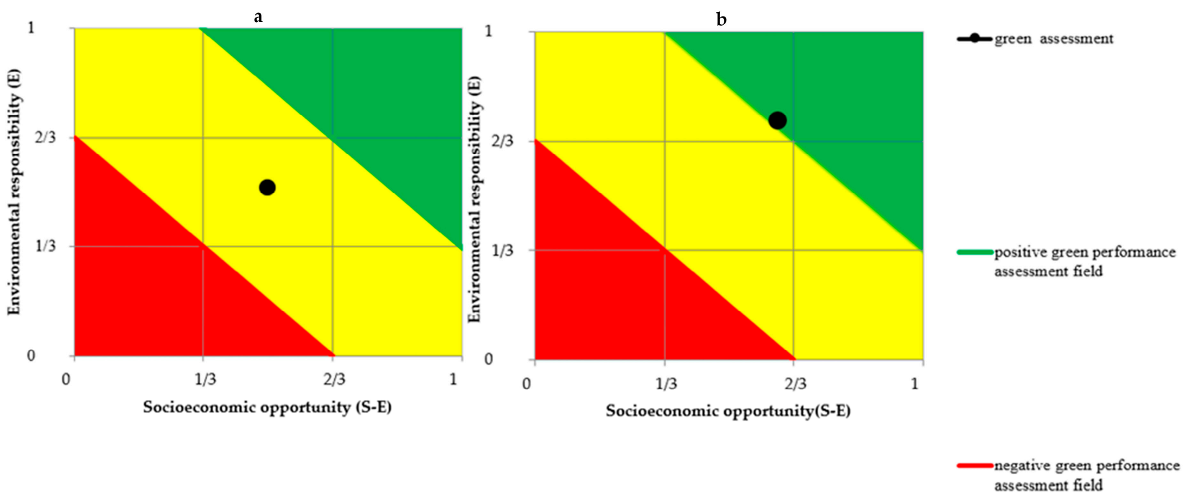

Figure 3. Interpretation of green performance values (**a**) for the baseline scenario; (**b**) for the improvement scenario.

4. Results

In this study, green manufacturing performance in heating boiler manufacturing is assessed. An evaluation scale of the internal and external criteria shown in Table 2 is applied to compare and assess company performance of manufacturing processes for baseline and improvement scenarios. A comparison of the performance of manufacturing processes using the evaluation scales for the internal and external criteria is shown in Table 2. The scale is represented by different sets of indicators for evaluating the greening performance and then translated into fuzzy numbers.

A comparison reveals the improvement scenario presenting a positive assessment performance, which is placed in the top right part of the portfolio matrix in the green zone.

The technology applied in manufacturing processes and expressed through integrated LCA-based indicators defines the performance of the company producing heating devices. Through the adoption of future competing, auspicious green techniques and technologies, a new future performance (improvement scenario) is generated. In this case, the performance of the company in terms of manufacturing processes shows its green performance resulting in a medium value of "aggregated" external environmentally criteria (between 0.33 and 0.67) and a high value of socioeconomic opportunity criteria (between 0.67 and 1). It presents that final criteria (crisp values w) are rational (0.729 and 0.625) respectively. By contrast, company performance achieves neutral assessment in the baseline scenario (0.510 and 0.500). The "larger values" of going green (0.729 and 0.625) compared to the baseline scenario values relate to the reduction of unnecessary produced waste (E3), for welding and cleaning processes; GWP (E5); respiratory effects (E6) indicators; as well as creating a healthy environment for employees (SE2) for all considered processes.

Here, the mean values of triangular fuzzy numbers was the measurement of criteria from experts' experience for the baseline scenario, where the TFN of "environmental responsibility" according to the expert, in his/her opinion, are (0.25; 0.542; 0.708) with the smallest value of 0.25, the biggest value of 0.708, and the median value -0.542, for "socioeconomic opportunity" with values (0.313; 0.50; 0.688). The other TFNs in the improvement scenario were obtained in the same way; here, they are (0.417; 0.792; 0.917) for "environmental responsibility" and (0.25; 0.688; 0.875) for "socioeconomic opportunity".

The implemented green manufacturing was selected to reduce environmental impact without having a negative effect on process quality. Some technologies reduced energy consumption, while others required more. Despite the energy requirements that were raised, it was still considered acceptable since the objective was to reduce pollution across the entire production process. Comparing indicators for scenarios, energy consumption (E1) and the recovery of materials (E2) is the most important contributor to greening enterprise for cleaning and panting or cutting, while for welding, the environmental performance impact has less importance. Neutral assessment may result from the minor nature of improvements to the manufacturing processes.

As a result, by looking at the evaluation of the enterprise performance (before and after), it is shown that the considered company is going green. It shows a movement of the bubble towards reaching the green zone which means an understanding of the current state of "greening" as well as identification of what kind of problems the company is presently facing.

As a body of knowledge for the best green practices grows and technologies for production performance improve, more ambitious indicators, such as production efficiency or the production orders' change rate, and internal logistics efficiency are to be expected. Improvements in processes are invaluable without potentially useful indicators when discussing sustainability, and they would help to increase the overall production efficiency. Production efficiency could be represented by the overall equipment performance (OEE) which can be measured for a single machine as well as for the overall plant (OPE-overall plant effectiveness). OEE indicates the gap between the initial and improved performance of a manufacturing process.

Every manufacturing plant modifies the way of calculating OEE in order to identify individual problems and underlying improvements that are needed to increase their own productivity. Hence, OEE could measure the proportion of scheduled time consisting of the time taken to deliver goods from suppliers and the time the machine is actually making parts.

However, although the concept behind OEE can be applied to the heating sector, OEE concentrates on the quality, performance and productivity of machines. Unfortunately, the proposed technological solutions are not supported by comprehensive manufacturing information. In addition, the manufacturing processes are not followed by any scheduling, neither are they monitored by any production systems.

In this research, technologies are not modeled as intelligent machines which can collect production data and control the machines. They ignore inefficiency in operational related losses and other resources of a production line, such as the usage of materials, the environment as well as man's efficiency. tOn the other hand, production efficiency indices are more applicable in a fully automated production environment to identify and optimize key performance indicators within a production line.

In this context, considered indicators are the main key process performance in modern industrial production to achieve the total quality for the overall production efficiency and to connect the elements between LCA-based indicators and the decision making process. This may be taken into consideration in the next review of the boiler production system.

5. Discussion

As an illustrative case study, the author applies the Quick Green Scan methodology to evaluate green performance in the enterprise that produces domestic central heating devices. The framework for green assessing of manufacturing processes is translated into a structure for LCA-based indicators, which is structured along the criteria: environmental responsibility representing pressures on the environment, which are considered to be crucial due to socioeconomic activities and socioeconomic opportunity indicators representing economic products.

These two criteria with their indicators were used to conduct Q-G-S performance evaluation, for the baseline scenario. Then, some possible areas for improvement in manufacturing processes were identified to perform a reassessment of the improvement scenario. The evaluation is based on combining the LCA-based indicator and the fuzzy set. Jolly's and Gladysz's approaches are used to draw practical insights for assessing green performance.

The reason for the analysis, both before and after changes, is to answer the question of whether the company acts upon the opportunity to be green and improve the environmental performance and how actions are contributing towards sustainability, maintaining the status quo or moving away from a green outcome. Answering these questions, the facility improves green performance by reducing pollution streams and improves the socioeconomic impact associated with production. The opportunity to be green lies in the implementation of changes in existing technology or environmentally friendly technology. The analysis of production processes presented above, and the proposal of green solutions focus mainly on waste and emission pollution and their removal and reduction.

By applying green technology, industrial plants can create an image of responsibility and appeal to environmentally conscious producer groups. Applying green processes to the workplace, the company creates a healthy environment for employees who suffer from respiratory and other health-related conditions, because in the green assessment, green manufacturing contains fewer pollutions. As with any investment, it is important to measure the success of green technology implementation using a number of key indicators based on LCA that measure the technology's effects on various aspects of company performance. In addition, the performance evaluation approach and its measurement based on LCA indicators should provide credible and comparable data for decision makers. A well-constructed measurement system should help manufacturing companies to manage green investments so that they improve and thrive. Companies utilizing green technology are seeing an increase in profits, not right after the implementation of the green changes, but in a long-term perspective by lowering the costs of protection of human health and environment, eventually bringing the company into a position of continual cost savings (energy, resources).

Because the objective of this paper is to assess and improve the overall green performance of the plant, certain improvements may actually increase the consumption of energy at specific processes.

Adding ventilation and heating systems requires new energy expenditures, but reduces the overall pollution produced by the plant. The design trend for industrial machinery is toward greater energy efficiency, but variability in cost, performance, durability, and use-specific efficiency are important factors in choosing systems. In addition, energy savings in manufacturing processes need to be considered for the entire operational life of the machine. Efficiency in the material use and energy consumption may vary by both the type of machines and processes they are used in. Depending on the process, one type of machine may be more efficient in its use of energy than another, but poorer in its effectiveness in material use. An efficient machine that creates the need for additional processing may lower the overall efficiency of the plant. If the same operation (such as cutting) is performed at two different manufacturing facilities or on two different machines, the power consumption may vary, due to the differences in the machines or manufacturing processes. In addition, material consumption and the generation of emissions stream may differ depending on materials selected and the methods used to produce parts.

As mentioned above, it is noted that the changes of manufacturing processes used to achieve green practices in large-scale industry can be successful also in small businesses for improving processes, including productivity and quality. Small- and medium-sized enterprises (SMEs) are not only well-represented in the green movement, but are also the largest supplier by volume in the heating sector. It needs to be noted that SMEs are attractive targets for innovative green projects because they are usually more able to react quickly and effectively to market changes. While governmental policies should promote the construction of more green factories, a greater challenge today is how to retrofit, convert, and install more efficient and "green" or cleaner equipment in existing manufacturing infrastructure of the enterprises. Better opportunities to enhance environmental responsibility are clearer when the whole industrial sector is taken into consideration.

Further research is needed to address these issues. In addition, indicators related the socioeconomic performance are not yet well established and should be incorporated in green performance evaluation. Companies must adopt indicators that add value from an economic perspective. Hence, it is necessary to find a consistent link of environmental responsibility indicators to the socioeconomic opportunity ones in terms of manufacturing processes.

Managerial implications could be generated from the technology or production knowledge database. This is useful when production department managers study multi-source, heterogeneous and real-time data of production and equipment operation. Production data can be used to track the in-process quality and manage production equipment in order estimate equipment wear, repair, and its maintenance. Furthermore, with the help of the production database, the energy efficiency of equipment could be increased through the optimization of production decisions (e.g., which machine should operate at what speed at what time) could be relatively easy to achieve.

Going beyond findings proposed by Anderson [74], the analysis of the company performance shows that the transformation toward a greener business model is a complex process. Thus, there is a need for more research on the movement toward green enterprise. It relies on reconfiguration of existing manufacturing processes for green practices in firms from the heating sectors.

The analysis shows a gap between the desired and actual level of changes, which are highlighted through technical solutions. The study identifies green actions by which decision makers attempt to reach the desired state of greening in economic and environmental terms.

However, some limitations should be addressed. First, the study was based on a single case study. Second, the methodology used was based on limited data available in the plant. The collection of data from experts may bias the results leading to different results. Third, the data provided limited ground to generalize the findings. This suggests the need to replicate and extend the research for greater understanding of each manufacturing process and to develop appropriate indicators. Fourth, the lack of indices for calculating production efficiency can seriously understate the improvement or technology input into the production process, thereby resulting in depreciated or exaggerated estimates of productivity change. Another limitation that is not uncommon is that some indicators turn out to be conflicting—improving one may worsen another (for example energy consumption).

Although this approach limits the possibility of generalizing the findings, the inquiry from the case study suggests a benefit of the Q-G-S methodology which could be incorporated in every company's analysis to leverage the green vision.

6. Conclusions

In this article, the Quick Green Scan methodology for improving green manufacturing performance evaluation is developed. The overall evaluation of the enterprise producing heating devices demonstrates the usage of the methodology, and simultaneously proves its practicality and validity. The evaluation shows that the Q-G-S can be used to effectively analyze manufacturing processes' performance toward being green. Therefore, this paper was focused on developing a green performance assessment of manufacturing processes which can be used by unified manufacturing indicators to improve and compare their green level and enhance their current level of performance.

The study seeks opportunities for environmental improvement by proposing technological changes to existing manufacturing processes. The investigation is done by analyzing how the enterprise is dealing with environmental issues, its technologies and what modernization or actions, or improvements could be proposed in order to make the state of a chosen enterprise green.

This methodology was structured to provide comparable scores of decision making related to green performance. This approach combines fuzzy sets and initial linguistic scales to construct a future decision-making evaluation system that would be used to help assess the implementation of cleaner manufacturing processes. The methodology, particularly quick and simple, is a practical tool for benchmarking not only within the heating industry but also useful in providing comparison of a facility's performances in other manufacturing sectors. From this study, it can be concluded that the enterprise in question is "effective" in its green manufacturing initiative. Company performance achieves positive assessment in the improvement scenario (0.729 and 0.625) and neutral assessment in the baseline scenario (0.510 and 0.500).

The neutral assessment for manufacturing (yellow zone) may result from pollution prevention actions performed by the considered company that use non-toxic chemicals as cleaners, degreasers and reduce the quantity of wastes.

The GWP (E5) and Respiratory effects (E6) as well as healthy environment for employees (SE2) indicators have the largest impacts on greening in heating boiler manufacturing after improving processes.

It can be concluded that the production performance efficiency measurement should include other production losses investigated to determine a total plant effectiveness in manufacturing. The practical performance efficiency measurement combined with other indices could be carried out in a future paper.

The evaluation of the company performance has shown that its decisions can contribute significantly to producing more environmentally friendly boilers through the creation of green processes. Therefore, this case study may provide motivation for other SMEs to evaluate their production processes and change their processes to become greener. Suggested changes in the existing manufacturing processes or implementation of green technologies give guidelines to achieve greening in environmental protection (responsibility) and socioeconomic opportunity.

Moreover, the presented Q-G-S methodology could be tailored to specific needs dependent on the technology used, company, market etc. Incorporation of the aforementioned "green" principles and their features to set assessment criteria and indicators in manufacturing processes might have significant influence in achieving green performance.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Rusinko, C.A. Green Manufacturing: An Evaluation of Environmentally Sustainable Manufacturing Practices and Their Impact on Competitive Outcomes. *IEEE Eng. Manag.* **2007**, *54*, 445–453. [CrossRef]
2. Zhang, Y.; Ren, S.; Liu, Y.; Si, S. A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products. *J. Clean. Prod.* **2016**, in press. [CrossRef]
3. Cheung, W.M.; Marsh, R.; Griffin, P.W.; Newnes, L.B.; Mileham, A.R.; Lanham, J.D. Towards cleaner production: A roadmap for predicting product end-of-life costs at early design concept. *J. Clean. Prod.* **2015**, *87*, 431–441. [CrossRef]
4. Rosen, M.A.; Kishawy, H.A. Sustainable Manufacturing and Design: Concepts, Practices and Needs. *Sustainability* **2012**, *4*, 154–174. [CrossRef]
5. Zhang, Y.; Wang, W.; Wu, N. IoT-enabled Real-time Production Performance Analysis and Exception Diagnosis Model. *IEEE TASE* **2016**, *13*, 1318–1332. [CrossRef]
6. Zhang, Y.; Qian, C.; Lv, J.; Liu, Y. Agent and cyber-physical system based self-organizing and self-adaptive intelligent shopfloor. *IEEE Trans. Ind. Inf.* **2016**. [CrossRef]
7. Chien, M.-K. Influences of green supply chain management practices on organizational sustainable performance. *Int. J. Environ. Monit. Prot.* **2014**, *1*, 12–23.
8. Rao, P. Greening production: A South-East Asian experience. *Int. J. Oper. Prod. Manag.* **2004**, *24*, 289–320. [CrossRef]
9. Wu, R.; Yang, D.; Chen, J. Social Life Cycle Assessment Revisited. *Sustainability* **2014**, *6*, 4200–4226. [CrossRef]
10. Ajukumar, V.N.; Gandhi, O.P. Evaluation of green maintenance initiatives in design and development of mechanical systems using an integrated approach. *J. Clean. Prod.* **2013**, *51*, 34–46. [CrossRef]
11. International Organization for Standardization (ISO). *ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO: Genève, Switzerland, 1997.
12. Toro, J.; Requena, I.; Duarte, O.; Zamorano, M. A qualitative method proposal to improve environmental impact assessment. *Environ. Impact. Assess.* **2013**, *43*, 9–20. [CrossRef]
13. Hui, I.K.; He, L.; Dang, C. Environmental impact assessment in an uncertain environment. *Int. J. Prod. Res.* **2002**, *40*, 373–388. [CrossRef]
14. Höjer, M.; Ahlroth, S.; Dreborg, K.H.; Ekvall, T.; Finnveden, G.; Hjelm, O.; Hochschorner, E.; Nilsson, M.; Palm, V. Scenarios in selected tools for environmental systems analysis. *J. Clean. Prod.* **2008**, *16*, 1958–1970. [CrossRef]
15. Sendra, C.; Gabarrell, X.; Vicent, T. Material flow analysis adapted to an industrial area. *J. Clean. Prod.* **2007**, *15*, 1875–1885. [CrossRef]
16. Mani, M.; Madan, J.; Leeb, J.H.; Lyons, K.W.; Gupta, S.K. Sustainability characterization for manufacturing processes. *Int. J. Prod. Res.* **2014**, *52*, 5895–5912. [CrossRef]
17. Baines, T.; Brown, S.; Benedettini, O.; Ball, P. Examining green production and its role within the competitive strategy of manufacturers. *J. Ind. Eng. Manag.* **2012**, *5*, 53–87. [CrossRef]
18. Figge, F.; Hahn, T. Is green and profitable sustainable? Assessing the trade-off between economic and environmental aspects. *Int. J. Prod. Econ.* **2012**, *140*, 92–102. [CrossRef]
19. Wong, C.W.Y.; Lai, K.; Shangc, K.; Lud, C.; Leunge, T.K.P. Green operations and the moderating role of environmental management capability of suppliers on manufacturing firm performance. *Int. J. Prod. Econ.* **2012**, *140*, 283–294. [CrossRef]
20. Salvado, J.A.; de Castro, G.M.G.; Navas-Lopez, J.E. Green corporate image: moderating the connection between environmental product innovation and firm performance. *J. Clean. Prod.* **2014**, *83*, 356–365. [CrossRef]
21. Florida, R. Lean and Green: The move to environmentally conscious manufacturing. *Calif. Manag. Rev.* **1996**, *39*, 80–105. [CrossRef]
22. Gungorand, A.; Gupta, S.M. Issues in environmentally conscious manufacturing and product recovery: A survey. *Comput. Ind. Eng.* **1999**, *36*, 811–853. [CrossRef]
23. Plehn, J.; Züst, R.; Kimura, F.; Sproedt, A.; Schönsleben, P. A method for determining a functional unit to measure environmental performance in manufacturing systems. *CIRP Ann. Manuf. Technol.* **2012**, *61*, 415–418. [CrossRef]

24. Sarkis, J. Manufacturing's role in corporate environmental sustainability: Concerns for the new millennium. *Int. J. Oper. Prod. Manag.* **2001**, *2*, 666–686. [CrossRef]
25. Kroes, J.; Subramanian, R.; Subramanyam, R. Operational Compliance Levers, Environmental Performance, and Firm Performance under Cap and Trade Regulation. *M&SOM-Manuf. Serv. Oper. Manag.* **2012**, *14*, 186–201.
26. Li, B. Study on Performance Evaluation of Enterprise Green Manufacturing Based on Fussy Integral. *Int. Rev. Comput. Softw.* **2012**, *7*, 773–778.
27. Ambec, S.; Lanoie, P. Does It Pay to Be Green? A Systematic Overview. *Acad. Manag. Perspect.* **2008**, *22*, 45–62.
28. Li, C.; Liu, F.; Tan, X.; Du, Y. A methodology for selecting a green technology portfolio based on synergy. *Int. J. Prod. Res.* **2010**, *48*, 7289–7302. [CrossRef]
29. Drira, A.; Pierreval, H.; Hajri-Gabouj, S. Facility layout problems: A survey. *Annu. Rev. Control.* **2007**, *31*, 255–267. [CrossRef]
30. Deif, A.M. A system model for green manufacturing. *J. Clean. Prod.* **2011**, *19*, 1553–1559. [CrossRef]
31. Linke, B.; Corman, G.J.; Dornfeld, D.A.; Tonissen, S. Sustainability indicators for discrete manufacturing processes applied to grinding technology. *J. Manuf. Syst.* **2013**, *32*, 556–563. [CrossRef]
32. Woerlen, C. Meta-Evaluation of Climate Mitigation Evaluations; Case Study: Poland's Heating Sector. Study for the Climate Change Evaluation Community of Practice. Available online: https://www.climate-eval.org/sites/default/files/studies/Meta-Evaluation%20-%20Poland%20Case%20Study.pdf (accessed on 11 September 2016).
33. Pons, O.; de al Fluente, A.; Aguado, A. The Use of MIVES as a Sustainability Assessment MCDM Method for Architecture and Civil Engineering Applications. *Sustainability* **2016**, *8*, 460. [CrossRef]
34. Fan, C.; Carrell, J.; Zhang, H.C. An investigation of indicators for measuring sustainable manufacturing. In Proceedings of the International Symposium on Sustainable Systems and Technology, Washington, DC, USA, 19–21 May 2010.
35. Feng, S.; Joung, C. An overview of a proposed measurement infrastructure for sustainable manufacturing. In Proceedings of the 7th Global Conference on Sustainable Manufacturing, Madras, India, 2–4 December 2009; pp. 1–6.
36. Lerkkasemsan, N.; Achenie, L.E.K. Life Cycle Costs and Life Cycle Assessment for the Harvesting, Conversion, and the Use of Switchgrass to Produce Electricity. *Int. J. Chem. Eng.* **2013**, *2013*. [CrossRef]
37. Schau, E.M.; Traverso, M.; Lehmann, A.; Finkbeiner, M. Life Cycle Costing in Sustainability Assessment—A Case Study of Remanufactured Alternators. *Sustainability* **2011**, *3*, 2268–2288. [CrossRef]
38. Sulga, M. Life Cycle Assessment (LCA) Based Environmental Impact Minimization of Solid Fuel Boilers in Lithuanian Industry. *Environ. Res. Eng. Manag.* **2011**, *4*, 74–84.
39. Glavic, P.; Lukman, R. Review of sustainability terms and their definitions. *J. Clean. Prod.* **2007**, *1*, 1875–1885. [CrossRef]
40. De Benedetto, L.; Klemes, J. The Environmental Performance Strategy Map: An integrated LCA approach to support the strategic decision-making process. *J. Clean. Prod.* **2009**, *17*, 900–906. [CrossRef]
41. Brander, M.; Tipper, R.; Hutchison, C.; Davis, G. *Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels*; Technical Paper TP-090403-A; Ecometrica Press: Edinburgh, UK, 2009; Available online: http://www.ecometrica.com/assets//approachesto_LCA3_technical.pdf (accessed on 11 September 2016).
42. Ekvall, T.; Weidema, B.P. System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. *Int. J. Life Cycle Assess.* **2004**, *9*, 161–171. [CrossRef]
43. Finnveden, G.A.; Hauschild, M.Z.; Ekvall, T.C.; Guine, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
44. Suh, S.; Huppes, G. Methods for Life Cycle Inventory of a product. *J. Clean. Prod.* **2004**, *13*, 687–697. [CrossRef]
45. Pacca, S. Life-Cycle Assessment (LCA) as a Management Tool: An Emphasis on Electricity Generation, Global Climate Change, and Sustainability. In *Handbook of Input-Output Economics in Industrial Ecology. Eco Efficiency Indicator in Industry and Science*; Suh, S., Ed.; Springer: Dordrecht, The Netherlands, 2009; Volume 23, pp. 247–261.

46. Kluczek, A. Assessment of the Eco-Efficiency of Manufacturing Processes Based on MFA-LCA-MFCA Methods. Available online: http://omicron.ch.tuiasi.ro/EEMJ/pdfs/accepted/561_521_Kluczek_14.pdf (accessed on 6 January 2016).
47. Westkämper, E.; Alting, A. Life Cycle Management and Assessment: Approaches and Visions towards Sustainable Manufacturing. *CIRP Ann. Manuf. Technol.* **2000**, *49*, 501–552. [CrossRef]
48. Schmidt, W.; Sullivan, J. Weighting in life cycle assessment in a global context. *Int. J. Life Cycle Assess.* **2002**, *7*, 5–10. [CrossRef]
49. Wang, X.; Chan, H.K.; Yee, R.W.Y.; Diaz-Rainey, I. Two-stage fuzzy-AHP model for risk assessment of implementing green initiatives in the fashion supply chain. *Int. J. Prod. Econ.* **2012**, *135*, 595–606. [CrossRef]
50. Vinodh, S.; Shivraman, K.R.; Viswesh, S. AHP-based lean concept selection in a manufacturing organization. *J. Manuf. Technol. Manag.* **2012**, *23*, 124–136. [CrossRef]
51. Hauff, M.; Wilderer, P.A. Industrial ecology: Engineered representation of sustainability. *Sustain. Sci.* **2008**, *3*, 103–115. [CrossRef]
52. Sudarsan, R.; Sriram, R.D.; Narayanan, A.; Sarkar, P.; Lee, J.H.; Lyons, K.W.; Kemmerer, S.J. Sustainable Manufacturing: Metrics, Standards, and Infrastructure. In Proceedings of the 2010 IEEE Conference on Automation Science and Engineering, Toronto, ON, USA, 21–24 August 2010; pp. 144–149.
53. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodologies. *Ecol. Indic.* **2012**, *15*, 281–299. [CrossRef]
54. Moldavska, A.; Welo, T. On the Applicability of Sustainability Assessment Tools in Manufacturing. *Procedia CIRP* **2015**, *29*, 621–626. [CrossRef]
55. Jiang, Z.; Zhang, H.; Sutherland, J. Development of an environmental performance assessment method for manufacturing process plans. *Int. J. Adv. Manuf. Technol.* **2012**, *58*, 783–790. [CrossRef]
56. Lu, T.; Gupta, A.; Jayal, A.D.; Badurdeen, F.; Feng, S.C.; Dillon, O.W.; Jawahir, I.S. A Framework of Product and Process Metrics for Sustainable Manufacturing. In Proceedings of the Eighth International Conference on Sustainable Manufacturing, Abu Dhabi, UAE, 22–24 November 2010.
57. Ziout, A.; Azab, A.; Altarazi, S.; Maraghy, W.H. Multi-criteria decision support for sustainability assessment of manufacturing system reuse. *CIRP J. Manuf. Sci. Technol.* **2013**, *6*, 59–69. [CrossRef]
58. Chhipi-Shrestha, G.K.; Hewage, K.; Sadiq, R. "Socializing" sustainability: A critical review on current development status of social life cycle impact assessment method. *Clean Technol. Environ. Policy* **2015**, *17*, 579–596. [CrossRef]
59. Gazi, A.; Skevis, G.; Founti, M.A. Energy efficiency and environmental assessment of a typical marble quarry and processing plant. *J. Clean. Prod.* **2012**, *32*, 10–21. [CrossRef]
60. Tyteca, D.; Carlens, J.; Berkhout, F.; Hertin, J.; Wehrmeyer, W.; Wagner, M. Corporate environmental performance evaluation: Evidence from MEPI Project. *Bus. Strategy Environ.* **2002**, *11*, 1–13. [CrossRef]
61. Kluczek, A. Application of best available techniques in an enterprise producing heating devices. *J. Clean. Prod.* **2014**, *83*, 444–453. [CrossRef]
62. Jolly, D. The issue of weighting in technology portfolio management. *Technovation* **2003**, *23*, 383–391. [CrossRef]
63. Jolly, D. Development of a two-dimensional scale for evaluating technologies in high-tech companies: An empirical examination. *J. Eng. Technol. Manag.* **2012**, *29*, 307–329. [CrossRef]
64. Gladysz, B.; Santarek, K. An assessment of technologies with wide range of impact. A case of RFID. *Procedia Manuf.* **2015**, *3*, 1966–1973. [CrossRef]
65. Zimmermann, H. *Fuzzy Sets Theory and Its Applications*, 2nd ed.; Kluwer Academic Publishers: Boston, MA, USA, 1991.
66. Papajorgji, P.; Guimarães, A.M.; Guarracino, M.R. *Enterprise Business Modeling, Optimization Techniques, and Flexible Information Systems*; IGI Global: Hershey, PA, USA, 2013; pp. 30–41.
67. Fasangarhi, M.; Roudsari, F.H. The Fuzzy Evaluation of E-Commerce Customer Satisfaction. *World Appl. Sci. J.* **2008**, *4*, 164–168.
68. A Study to Examine the Costs and Benefits of the ELV Directive—Final Report Annexes. Annex 5—Environmental Impacts Analysed and Characterisation Factors. Available online: http://ec.europa.eu/environment/waste/pdf/study/annex5.pdf (accessed on 11 September 2016).

69. Rączka, J. The cost-effectiveness analysis—A superior alternative to the cost-benefit analysis of environmental infrastructure investments. In Proceedings of the Fifth European Conference on Evaluation of the Structural Funds "Challenges for Evaluation in an Enlarged Europe", Budapest, Hungary, 26–27 June 2003.
70. Soltani, A.; Sadiq, R.; Hewage, K. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. *J. Clean. Prod.* **2016**, *113*, 388–399. [CrossRef]
71. Rogowski, W. *Account of Investment Efficiency*; Kluwer: Cracow, Poland, 2008. (In Polish)
72. Kluczek, A. Application of multi-criteria approach for sustainability assessment of manufacturing processes. *Manag. Prod. Eng. Rev.* **2016**, *7*, 62–78. [CrossRef]
73. Pfeiffer, W.; Metze, G.; Scheider, W.; Amler, R. *Technologie Portfolio zum Management Strategischer Zukunftschaeftsfelder*, 6th ed.; Vanden-hoeck & Ruprecht: Goettingen, Germany, 1991; p. 102.
74. Anderson, R. *Mid-Course Correction: Towards a Sustainable Enterprise: The Interface Model*; Chelsea Green Publishing Company: White River Junction, VT, USA, 1998.