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A General Framework for Sustainability Assessment of Sheet Metalworking Processes

Hamed Gholami [1,*], Muhamad Zameri Mat Saman [1], Safian Sharif [1], Jauharah Md Khudzari [2], Norhayati Zakuan [3], Dalia Streimikiene [4,*] and Justas Streimikis [5,6]

1 Department of Manufacturing & Industrial Engineering, School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), Johor 81310, Malaysia; zameri@utm.my (M.Z.M.S.); safian@utm.my (S.S.)
2 Department of Bioresource Engineering, Macdonald Campus, McGill University, 21,111 Lakeshore Road, Sainte-Anne-de-Bellevue, QC H9X 3V9, Canada; jauharah.mdkhudzari@mail.mcgill.ca
3 Azman Hashim International Business School, Universiti Teknologi Malaysia (UTM), Johor 81310, Malaysia; norhayatimz@utm.my
4 Lithuanian Energy Institute, Breslaujos 3, LT-44403 Kaunas, Lithuania
5 Lithuanian Institute of Agrarian Economics, A. Vivulskio g. 4A-13, 03220 Vilnius, Lithuania; justas.streimikis@gmail.com
6 University of Economics and Human Science in Warsaw, Okopowa 59, 01-043 Warsaw, Poland
* Correspondence: ghamed@utm.my (H.G.); dalia.streimikiene@knf.vu.lt (D.S.); Tel.: +60-116-126-1210 (H.G.); +84-370-6140-3424 (D.S.)

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Abstract: The sheet metalworking industries possess minimal knowledge in the area of sustainability despite having served as sub-contractors to various industrial sectors. This also highlights that suitable indicators for measuring the sustainability performance of sheet metalworking operations are poorly addressed. As sustainability assessment is regarded as a vital part of sustainable development, this paper has been aimed at establishing a general framework for sustainability assessment of sheet metalworking processes. The main attention was paid to two important processes—the cutting operations with a CNC turret punch press machine and sheet metal bending operations with CNC press brake machine. Stepwise guidelines to implement the proposed framework in sheet metalworking industries are consequently presented. Besides, this study contributes to developing an applicable sustainability indicator set for assessing such manufacturing processes. It makes a valuable contribution to advancing the narrow body of knowledge on the under-researched scope.

Keywords: sustainability assessment; framework; manufacturing processes; indicator set; sheet metalworking operations

1. Introduction

A paradigm shift from the conventional and cost-intensive end-of-pipe pollution control to a more economical solution justifies the development of sustainability assessment frameworks for manufacturing processes [1,2]. The adoption of strategic frameworks for 'sustainability assessment', which is regarded as a vital part of sustainable development [3], can contribute to industrial decision-makers and policy-makers to decide what improvement actions are needed to be taken into consideration to make their manufacturing processes more sustainable [4]. Although the definition of a sustainable manufacturing process is numerous and differs among researches [5,6], it is important to apply a more accurate definition for developing an effective assessment framework [7,8]. The definition outlined by the U.S. Department of Commerce [9]—the creation of manufactured products through a chain of processes bringing minimal negative impacts towards the environment; conserving energy and natural resources keeping in mind the societal importance, such as employee safety and sound economics—is found to be more suitable in the context of this research. However, the development of a sustainable manufacturing process not only provides industry with a competitive edge but also becomes a cost-effective road map for improving their manufacturing processes' performance according to the triple bottom line requirements [10,11].

Manufacturing processes are classified into various types of operations, often being grouped into categories, such as shaping, property enhancing, surface processing operations, permanent joining, and mechanical fastening. These processes can be further divided into two groups of manufacturing processes at a much higher hierarchy—processing operations and assembly operations (cf. [12]), as shown in Figure 1. The processing operations change the shape of a product to a more advanced state close to the finished state, and the assembly operations bring two individual entities together through various types of joining and mechanical fastening processes, such as welded automobile car chassis. Sheet metalworking is a processing operation since it resembles the process of transforming raw sheet metal to a more advanced state close to a finished part shape through a series of material removal and deformation processes. The material-removing process in sheet metal is done through shearing or blanking operations, and the shaping process is done through bending operations. Sheet metalworking operations include laser cutting, punching, deep drawing, air bending, incremental forming, etc. [13]. In this regard, the research for this article was built upon the punch press and air bending since these two operations are considered to be most important by sheet metalworking small and medium-sized enterprises [13,14]. Due to the increase in steel prices, engineers need to limit the material cost, reduce waste, and explore better integration between these two processes. This fact reemphasizes the importance of having a sustainability assessment framework for sheet metalworking operations.

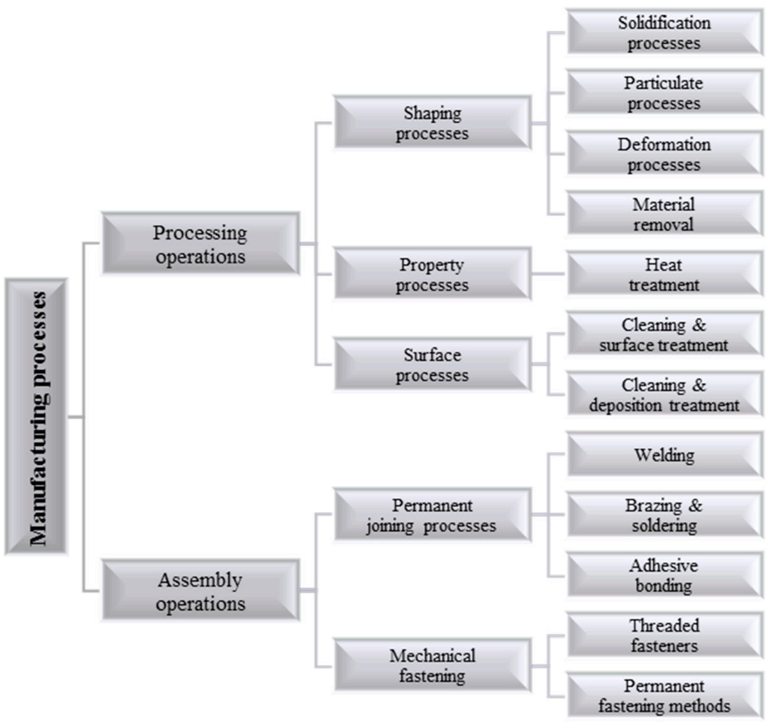

Figure 1. Classification of manufacturing processes [12].

This study seeks to make a valuable contribution, as there are only limited studies available for presenting a systematic methodology/framework for assessing sustainability for manufacturing processes [3,8,15,16]. Furthermore, the available assessment frameworks revolve mainly in the field of machining [13], and there is no available framework for assessing sustainability in sheet metalworking manufacturing processes. This indicates that suitable indicators for measuring the sustainability of sheet metalworking operations have been poorly addressed. Ultimately, all the assessment frameworks contribute to establishing a more general framework rather than a localized one for any given manufacturing process (e.g., [3]). However, the requisite for manufacturing processes taking into account the triple bottom line requirements is nowadays becoming very vital [17,18], and it is more immense for engineering supporting industries that do not have rights on the product design. A thriving implementation of sustainable manufacturing strategies in any industry requires an effective analytic assessment framework indicating how far the company is from achieving its sustainability goals, objectives, and targets [8,19,20]. In discussions concerning sustainable manufacturing processes, for example, supporting industries such as sheet metalworking companies, it can be seen that the likelihood of making any changes to the product design is very remote. These industries manufacture the products as designed by the original equipment manufacturer. The importance of this research is, therefore, to provide a methodological framework for assessing the sustainability performance of a manufacturing process without attempting to change the product design. It is believed that this is handy for any sub-contracting industries, such as sheet metalworking operations, in particular, when the main attention is given to two important operations—cutting operations with a CNC turret punch press machine and sheet metal bending operations with CNC press brake machine. Besides, the study has also attempted to contribute to developing the sustainability assessment indicators for manufacturing processes by reviewing the contemporary literature on the topic.

The rest of this paper has been structured as follows: In Section 2, some of the available sustainability assessment frameworks are reviewed, all the gaps are discussed, and their requirements for measuring the sustainability of sheet metalworking manufacturing operations are explained. A framework for assessing the sustainability of a manufacturing process is presented in Section 3, and its applicability for sheet metalworking processes, especially in cutting and bending operations, is also detailed. The required metrics/indicators for the sustainability assessment are briefly described. Finally, the conclusion and future research directions proposed from this study are outlined in Section 4.

2. Literature Review

Although the terms 'Sustainable Development' and 'Sustainability' have often been used interchangeably, there is an inherent difference between them—sustainable development is the path or process to sustainability, i.e., the capacity for continuance into the long-term future or the ideal dynamic state [21,22]. Given the growing global viewpoints on sustainable development, as popularly outlined by the World Commission on Environment and Development (WCED) [23] as "Our Common Future", a large number of the scientific communities have been involved in embedding this phenomenon in the manufacturing context. It becomes more intense when it was pointed out the manufacturing sector is the major contributor to our common future during the Earth Summit, held in Rio de Janeiro, Brazil, in 1992 [24].

Since then, a revolutionary change has appeared in this field; from the 'traditional manufacturing' which is substitution-based to 'lean manufacturing' which is waste reduction-based, then 'green manufacturing' (popularized in the 1990s) which is environmentally-benign and based on the 3Rs (reduce, reuse, recycle), and, today, 'sustainable manufacturing', which involves sustainable products, processes, and systems in its core through focusing on the 6Rs—reduce, reuse, recycle, recover, redesign, and remanufacture [25]. Figure 2 shows a holistic perspective of sustainable manufacturing elements, where the union generated by the overlap among products (value design), processes (value creation), and systems (value recovery) are made based on the 6R concept to fulfill the triple bottom line requirements. It highlights that the assessment and development of these three functional elements are essential to achieve a more sustainable-based state.

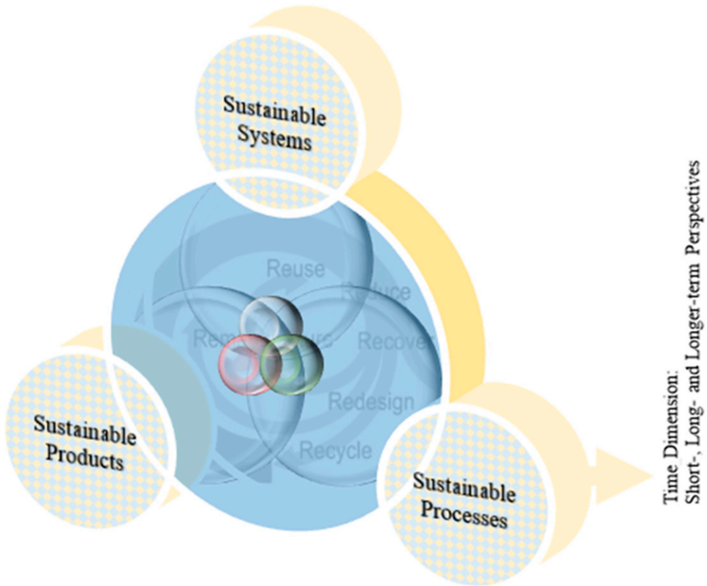

Figure 2. A perspective of sustainable manufacturing elements, from the unsustainable status quo to a more sustainable-based state.

Sustainability Assessment of Manufacturing Processes

Sustainable processes are regarded as a major functional element to sustainable manufacturing development (Figure 2). To develop sustainability into manufacturing processes, six interacting factors among the various influencing factors have been significantly considered by previous researchers, as shown in Figure 3. Initial investigations [25–28] outlined it as a process that improves environmental friendliness (desired level: maximum), reduces manufacturing cost (desired level: minimum), reduces energy consumption (desired level: minimum), reduces wastes (desired level: minimum), enhances operational safety (desired level: maximum), and improves personnel health (desired level: maximum). This requires a more accurate quantitative assessment framework, and it must be economical for the industries to measure.

Figure 3. Major factors affecting sustainable manufacturing processes.

Sustainable manufacturing process assessment seeks to measure the sustainability performance of a manufacturing process chain [8,29], in some cases, without even considering making changes to the product design. The types of material, thickness, or even the physical shape of the product are sometimes excluded from the assessment even though these characteristics have been regarded as indicators for developing sustainable manufacturing processes, e.g., in the blanking operations, the energy requirement for a cold roll sheet compared to stainless steel sheet is so much less. In this case, material properties cannot be considered as an indicator of a sustainable manufacturing process since this parameter is beyond the control of the sheet metalworking industries. Therefore, designing sustainability assessment frameworks can be very challenging since all the factors or indicators influencing a manufacturing process are very relative and case-specific with different expectation levels as well as differing in product, process, or the whole manufacturing systems [7,30,31].

There are many sustainability indicators that can be effectively applied to the sustainability assessment of manufacturing processes. From the National Institute of Standards and Technology (NIST), Joung et al. [32] reviewed eleven publicly available indicator sets, as presented in Figure 4. They have accordingly developed a comprehensive sustainability indicator set that categorizes indicators into appropriate classes and subclasses, believing that it will be extremely helpful in the selection procedure of indicators. However, to identify which indicators to choose and how to analyze them to evaluate a sustainable manufacturing process always pose challenges to the practitioners in various manufacturing industries [3,28,33].

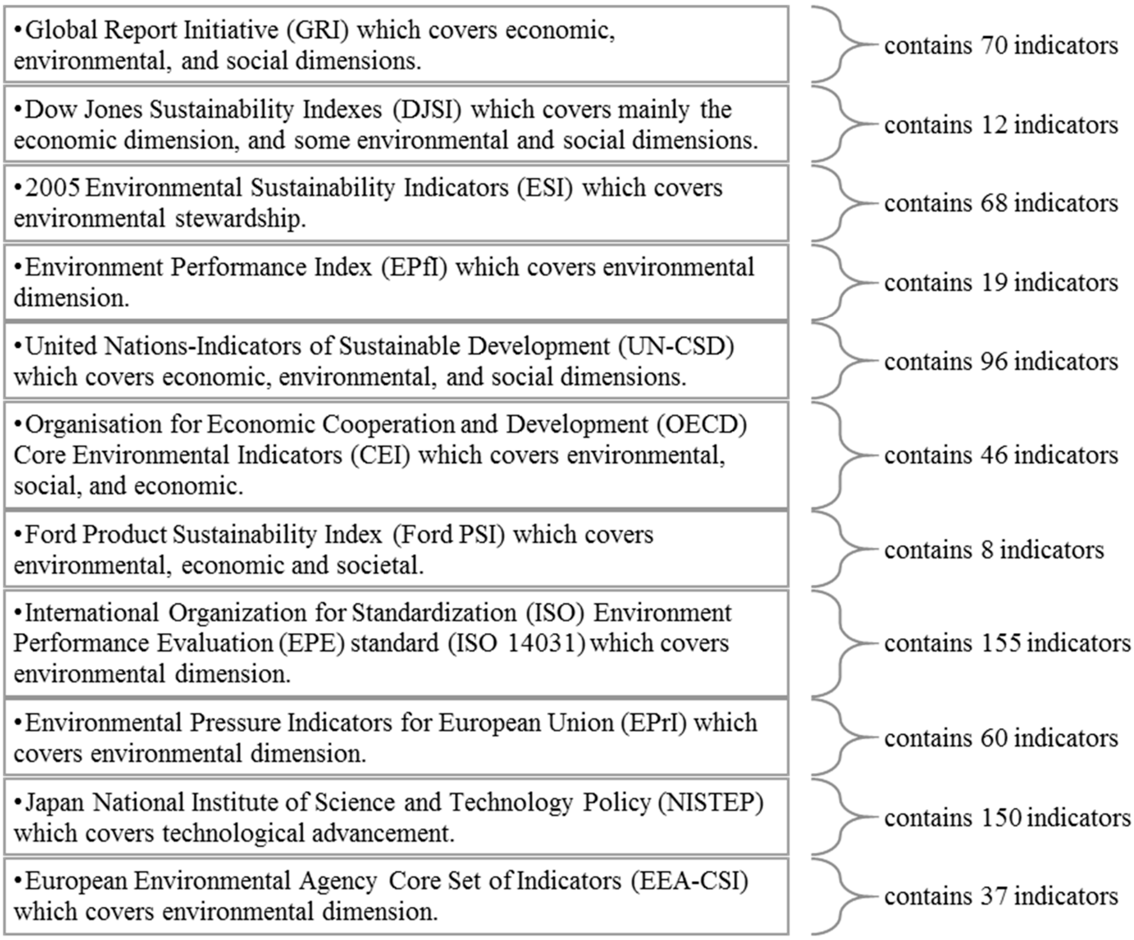

Figure 4. Common indicator sets.

In nutshell, what is sought in a sustainability assessment of sheet metalworking operations is the core indicators that can be optimized by the industries to improve performance, such as integrated production planning between the cutting and bending operations which will reduce the make-span and a reduced set-up time [13]. In sheet metalworking operations, optimal cutting and bending operations will only be achieved with good sheet metalworking nesting operations and a good production plan at the press brake machine which minimizes the number of steps required. Furthermore, sheet metalwork parts do not have any other process alternatives which can be adopted or even evaluated for a more sustainable performance unlike in the case of chemical industries, which always have several alternatives to manufacturing processes for a single product. For instance, a sustainability assessment was conducted on a chemical process for the synthesis of silica gel nanoparticles through three different methods, which is known as the sol–gel method, flame methods involving tetraethylorthosilicate (TEOS) and hexamethyldisiloxane (HMDSO) [34]. From the sustainability assessment, the process was ranked as HMDSO > TEOS > sol–gel overall. Martins et al. [35] conducted a similar kind of sustainability assessment on a chemical processing for chlorine via three different alternatives (using membrane, diaphragm, and mercury cells) and acetone/chloroform mixture separation process via two different solvents (benzene and methyl-n-pentyl-ether). At the end of these studies, one of the proposed alternatives yielded a more sustainable process, then was adapted as the favorable process.

As mentioned earlier, in the case of sheet metalworking parts, looking for alternative processes is certainly impossible, and the only method for achieving a more sustainable condition is via process optimization. Singh et al. [29] compiled details on the number of efforts done for developing indicators and frameworks for sustainable development. In this series, the assessment models which are described under the environmental indices for industries—co-Points, Eco-compass, Eco-indicator 99, Environment Assessment for Cleaner Production Technologies, and COMPLIMENT—show relevance towards manufacturing process assessments, but none of them provide an assessment model just for the manufacturing process concerning the three pillars of sustainability. In many ways, it does assist in the understanding of all the various types of sustainability indices available to the industries in a more concise way along with some detailed explanation on the composite indicators for sustainability. In another series of papers, Singh et al. [36] provided an assessment model for developing a composite sustainability performance index (CSPI) that addresses the sustainability performance of steel industries. The comprehensive methodology begins with the indicators' selection process to the development of the final sustainability composite performance index with a case study of the steel industry in India. The final CSPI is calculated from the aggregation of Liberator and Z score ratings with the aid of the analytical hierarchy process (AHP), which assists in determining the weights for both qualitative and quantitative indicators. Finally, the model was then applied to real-time steel manufacturing industries, and the CSPI was evaluated collectively for 4 years. The disadvantage with this assessment is the biasness issues resulting during the AHP evaluation, which determines the relative weights of the indicators.

Kim et al. [37] used the life cycles assessment (LCA) and design for environment (DFE) for measuring and designing a more sustainable manufacturing process for producing forklifts. The assessment was applied to design a more sustainable painting process by developing a new high solid point in the replacement of the solvent paint, which was found to be more harmful to the environment. This new approach is known as a product-focused approach since it evaluates the environmental impact of a product for the entire life cycle. A process-type environmental impact consideration only takes place while the product is being manufactured, and most of the time, this is known as end-of-pipe solutions. A product-type consideration takes into account all the environmental, economic, and societal factors right from the very beginning stage when the product is being designed. This includes the impacts caused during raw material extraction and also when the product is manufactured before it is put into mass production. In this study, the assessment was done on the unit processes involved in manufacturing a forklift. A brief description of the various unit processes involved in manufacturing a forklift is first laid out since the boundary of the study was only focusing on unit processes without even considering raw material acquisition and processing. First, an LCA was applied to collect all the inventory analysis, which shows the damages brought by all the process to seven different categories of environmental impact and found that the unit processes of cutting and welding and painting caused the highest environmental impact. It was certainly a tough task to reduce the environmental impact due to cutting and welding since no replacement was possible for steel as raw material, so the DFE was applied to the painting unit process, which was the next highest element recorded as a major source to the environmental impact. Consequently, a new high solid paint was designed, which eventually reduced the overall environmental impacts by 20%. The disadvantage seen in this model is that the assessment does not include aspects from the other two pillars of sustainability (i.e., economical and societal), and this methodology is also not applicable for a sub-contracting manufacturer, where they are usually not allowed to make any changes on the product design.

Manufacturing processes are numerous, and all of them differ between one another in various aspects, such as methodology, equipment used, production setups and conditions, safety, shapes of raw material, etc. Furthermore, to manufacture a single part, it does not only end with a single machine tool, for example, even production of a single nut, starts with the process of CAD design, material selection, material removal processes, milling, boring, and finally, surface treatment preventing rusting and a permissible cosmetic. It is a tough task to define elements contributing to a sustainable manufacturing process without any guide since some of these elements are not applicable to any other manufacturing process. Modeling the scientific methodology for measuring each of the selected elements makes the situation more challenging [25]. Despite this impediment, it is still possible to have a common framework to assist in identifying the elements for any kind of manufacturing process. Machining industries have been an important economic catalyst for any fast-developing countries, which accounts for about 5% of gross domestic product [26], while in Malaysia, nearly USD 428 million worth of exports is being contributed by this sector [38].

Jawahir et al. [25] defined six sustainability elements for a machining process, as shown in Figure 3, and established a framework to assess the sustainability of a machining process based on the selected elements. In the assessment framework, some of the elements, such as machining cost, energy consumption, and waste reduction, can be modeled quantitatively, whereas environmental friendliness, personnel health, and operational safety need to be modeled qualitatively using tools such as fuzzy logic. The assessment model was further supported with an optimization formulation describing all the constraints which need to be maximized and minimized. The assessment framework was then applied to a case study and results obtained from the fuzzy logic assessments known as the Mamdani method. The result obtained from the study indicates a significant improvement in the overall sustainability after installing additional auxiliary equipment, which served to improve the usage of coolants. The assessment for the non-deterministic was done for both types of processes since it does not depend on the number of passes. For the analytical elements, the optimization techniques were done with the techniques known as the simulated annealing algorithm, and the results prevailed to be the most sustainable conditions that need to be applied in both the rough and finish passes [39].

Energy is one of the most popular elements which all types of manufacturing industries would like to make more sustainable since the impacts on the environment are not in favorable conditions. In an energy audit study among the Malaysian industrial sector, it was found [38] that fabricated metal products are the second-highest industries consuming energy (166 MWh/100 ton). Rajemi et al. [40] formulated a mathematical model that enables the optimization of energy for any machining operations by identifying the most appropriate cutting velocity (Vc) and spindle speed. This type of science-based mathematical model will assist in reflecting all the aspects which need to be optimized for achieving sustainable conditions. Other types of sustainable machining processes as an alternative replacement to conventional flood machining are cryogenic (Cryo) and high-pressure jet assisted machining (HPJAM). Some of the potential benefits that can be obtained from cryogenic machining are [41] that it is cleaner, safer to the employee, and serves efficient waste management; it improvises material removal rate (MRR) without affecting tool wear and better productivity, the positive sign of tool life due to lower abrasion and chemical wear, and it also increases the quality of the product.

Consequently, there are a number of papers that deal with sustainability models but do not describe the detailed aspects of the sustainable manufacturing process [15,34,35,41–53]. All of these papers show that it is not possible to have a common sustainable assessment framework just meant for the manufacturing process. Minimal efforts can be seen for developing a common framework assessing the sustainability of a manufacturing process for a given product. There are some sustainability models that involve product design elements as one of the improvement parameters for achieving more sustainable unit processes [54–57]. Most of the developed models have revolved around specific machining processes, such as turning, grinding, or milling [29,31,58–63]. Lu et al. [31] proposed a metrics-based approach to assess the sustainability performance of a drilling process according to sustainable manufacturing elements, as shown in Figure 3. Lu and Jawahir [60] used a metrics-based process sustainability index assessment to experimentally evaluate the performance of cryogenic machining. Bhanot et al. [62] developed a framework for turning processes' sustainability assessment in the automobile industry. These investigations have assessed the sustainability performance of various machining processes; however, there is not a unified assessment framework to follow and implement.

Although other processes, such as casting, joining, forming, and shaping, have negative impacts on the triple bottom line, limited efforts have been made in their assessment [19,29,64–68]. It has been observed that casting and some joining processes, such as welding, consume a considerable amount of energy and involve safety risks owing to the workers' exposure to toxic gases and high temperatures. To this end, Singh et al. [29] proposed a Sustainability Analyzer, which is a computer-aided system, to analyze three sustainability indicators—energy use, solid waste, and carbon emissions—in the die casting process. Chang et al. [66] applied the tools of life cycle assessment (LCA) and social life cycle assessment (SLCA) to assess the environmental and social impacts of welding technologies. Sproesser [65] used a weight space partitioning sustainability assessment tool to evaluate two welding processes. Ingarao et al. [19] pointed out there is a lack of knowledge in sheet metal forming processes. In 2012, they compared energy and material used between a single point incremental sheet forming operation and a classical stamping operation based on experimental and numerical data [67]. Ingarao [68] focused on the analysis of metal shaping processes at the unit process level and highlighted its role in putting in place circular economy practices, outlining research needs as such.

Going through the literature indicated that most of the research done concentrated on sustainable product design or specific manufacturing processes, such as machining. According to Huang and Badurdeen [33], there are no available comprehensive frameworks for sustainable manufacturing performance assessment at the system level, in particular, at the production line and plant levels. The sheet metalworking industries, which are considered as one of the biggest industries in the sectors of fabricated metal products [13], possess very little knowledge in the area of sustainability despite having served as sub-contractors to automotive, aerospace, and electrical industries. In this context, Duflou et al. [69] presented a view on the environmental aspect of sheet metalworking processes and concluded that there are significant opportunities to improve sheet metalworking operations from an energy consumption point of view. This also highlights that the suitable indicators for measuring the sustainability performance of sheet metalworking operations have poorly been addressed.

3. A Framework for Sustainability Assessment of Sheet Metalworking Processes

Sustainability assessment is defined as an appraisal methodology [4]. Many researchers have often incorporated the term "framework" into this concept without a proper definition. Aalbregtse et al. [70] described framework as "a clear picture of the leadership goal for the organization and should present key characteristics of the to-be style of business operations". Popper [71] referred to it as "a set of basic assumptions or fundamental principles of intellectual origin in which discussions and actions can proceed". In this study, it is believed that a framework addresses 'how to assess' and performs an overall way forward. The importance of having a framework is to ensure the right steps are taken to reach the final objective of the project. One of the key factors for designing a successful framework is that it be simple enough without any lengthy prescription and not be costly to implement [71].

It should also be suitable for small businesses since most of the sheet metalworking operations fall under the classifications of small–medium enterprises (SMEs).

Figure 5 presents a framework for assessing the sustainability of sheet metalworking processes with a clear boundary, illustrating how each step works by being broken down into stages. The boundary of assessment needs to be explained to ensure the developed framework meet the goal of a sustainable manufacturing process [32]. The assessment must clearly distinguish between sustainable manufacturing elements, i.e., sustainable products, processes, and systems (See Figure 2) to avoid any complexity during the selection of indicators. The goal of sustainable manufacturing processes is to establish the processes that consume very little energy and produce zero or near-zero waste [49] as well as improve environmental friendliness, reduce manufacturing cost, enhance operational safety, and improve personnel health (See Figure 3).

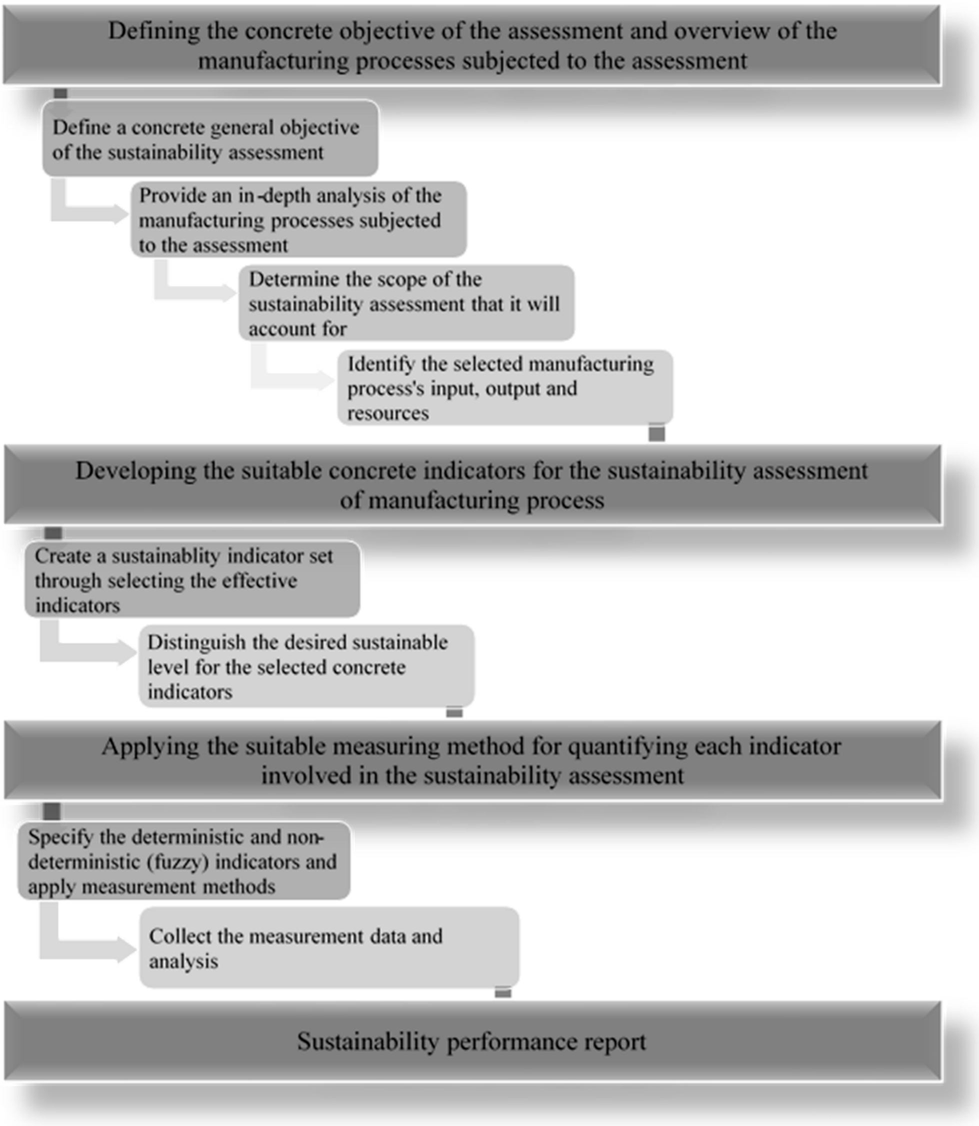

Figure 5. Developed framework for sustainability assessment of sheet metalworking processes.

3.1. Step 1: Defining the Concrete Objective of the Assessment and Overview of the Manufacturing Processes Subjected to the Assessment

3.1.1. Concrete General Objective of the Sustainability Assessment

Defining a concrete general objective is the first step for developing a sustainability assessment methodology since it determines many other characteristics of the assessment. Without a proper definition of the general objective, the sustainability assessment will lead to diversifying into the opposite direction of the goal. The objective of the assessment describes the relationship with its indicators, how, when, and by whom the assessment is conducted and finally assists in distinguishing the type and level of analysis required before publishing the final report on the sustainability [72]. The general objective will be guided by the following steps in the frameworks, covering questions such as how comprehensive it needs to be, explaining the requirement of integration of other types of assessments, such as an environmental impact assessment (EIA), strategic environmental assessment (SEA), social impact assessment (SIA), multi-criteria analysis (MCA), life cycle assessment (LCA), etc., and defining the focus of the assessment [4,32,73]. The aim of this research is to provide a framework for assessing the sustainability performance of sheet metalworking operations. In most cases, the sheet metal cutting operations are done with CNC laser cutting machines or turret punch press machines, and bending operations are done with a CNC press brake machine. But it does not stop at these two operations. It is usually done with a welding operation followed by grinding/deburring, press-fitting of fasteners, and finally, surface finishing. Therefore, the concrete objective for the case study was to assess the cutting operations with a CNC turret punch press machine and sheet metal bending operations with a CNC press brake machine, due to their importance in sheet metalworking industries. All the relevant parameters which influence these two processes were accordingly considered for the final optimization performance report.

3.1.2. In-Depth Analysis of the Manufacturing Processes Subjected to the Assessment

In the same step, an in-depth analysis of the manufacturing processes that are subjected to the assessment needs to be performed based on the experts' opinions, who are involved in the manufacturing processes that are being assessed. In the case of the sheet metalworking operations, the analysis has been applied to the cutting (shearing or blanking operations) and bending processes. Having an in-depth analysis of the cutting operations, which is often referred to it as the shearing or blanking operations, with a CNC turret punch machine, will give the important characteristics and parameters that need to be considered during the assessment. Similarly, with the bending operations with a CNC press brake machines, the resulting analysis will lead to knowing more about the important parameters that need to be sustained during the operational works.

3.1.3. Scope of the Sustainability Assessment

The next stage is to define the scope of the assessment to avoid any complexity during the assessment process and, most importantly, when selecting suitable indicators. The scope determines the levels where the sustainability assessment lies and what needs to be considered in the chain of the manufacturing processes [2]. Just as in the case of sheet metalworking production, the process of manufacturing the raw material, processes taking place at the supply chains, processes for disposing the various wastes from the production are not taken into consideration in the sustainability assessment. The focus is only on the aspects that are required for manufacturing the sheet metal parts involving the cutting and bending processes. Thus, the other manufacturing processes involved in setting up or organizing the manufacturing inputs and resources for producing sheet metal parts cannot be considered, e.g., the raw sheet metal manufactured by the iron core process and disposing or recycling the wastes from the turret punch machine or press brake machine is not part of the sustainability assessment at this period.

According to Sala et al. [4], an adequate scope addresses "both short- and long-term effects of current policy decisions and human activities, and appropriate geographical scope, to capture both their local and their global effects". It is pointed out that a sound sustainability performance report should meet the stakeholders' needs and satisfaction [1,32,46]. Thus, this stage should also consider the identification of stakeholders to avoid any uncertainty during the assessment process; however, uncertainty is an issue particularly for policy- and decision-makers [3,4], who have to decide whether the actions should be taken to enhance the certainty that objectives will be met. As stakeholders' identification and legitimacy is critical and poses serious challenges for sustainability assessment, the developed strategies in the post-normal science context and directed towards trans-disciplinarity look to enlarge stakeholder's involvement. To this end, defining sustainability goals with stakeholders in mid-term planning at a local level, incorporating the requirements of stakeholders in technological sustainability assessment, and engaging supply chain stakeholders in performing the development and assessment of a project have been outlined by Sala et al. [4]. Therefore, taking into account that appraisal methodological alternatives are associated with the acceptance of stakeholders and also their potential involvement in the assessment procedure, the subsequent criteria have been deemed appropriate to this context [4,46]: (1) encourage stakeholder interaction during the assessment procedure; (2) make a collaborative problem-solving approach for the project; (3) provide transparent access to information for stakeholders so as to enable them to review the projections made and the expected results of decisions; and (4) present a clear interpretation of outcomes and implications to the stakeholders.

3.1.4. Identifying the Manufacturing Process's Inputs, Outputs, and Resources

The final stage in step 1 of the proposed framework is to know and identify what the inputs, outputs, and resources required for the manufacturing processes that are being assessed are (Figure 6). Manufacturing inputs always refer to the ingredients that are required to manufacture the parts. In the case of sheet metal parts, the major material is the mild steel sheet, and the energy consumption is significant in some processes. Resources for manufacturing processes refer to indirect ingredients, such as machinery, tooling, etc. Finally, the outputs are the wastages and emissions that are yielded during the process of manufacturing the parts. Addressing all these three elements can only be done by conducting an in-depth analysis of the manufacturing processes, and these are important when drawing the interconnection with their impacts on the triple bottom line. For example, a better nesting efficiency (e.g., a reduction in the generated amount of waste) in a sheet metal cutting operation with a CNC turret punch press machine results in saving relevant amounts of material and related environmental impacts. The inputs and outputs which go across the process's boundary (Figure 6) are accordingly specified to quantify all the relevant indicators [35,69]. Their data for the aim of the assessment can be obtained from detailed inventory analysis to ensure good data quality.

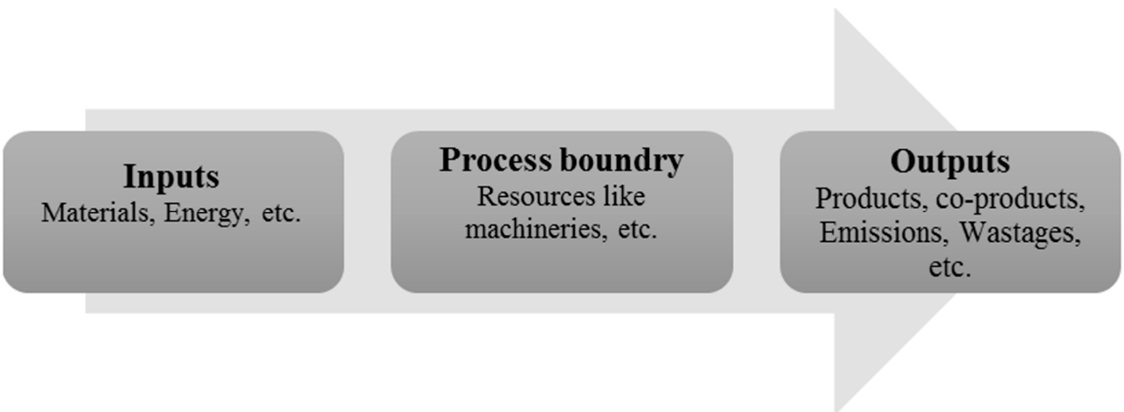

Figure 6. Inputs and outputs going across the process boundary.

3.2. Step 2: Developing the Suitable Concrete Indicators for the Sustainability Assessment of Manufacturing Process

3.2.1. Creating a Sustainability Indicator Set through Selecting the Effective Indicators

It is important to understand the definitions and classifications of indicators before going into the subject of developing an indicator set for assessing the sustainability of a manufacturing process. An indicator is a parameter or variable that indicates the state (content indicator) or behavior (performance indicator) of a system [45]. It requires a metric to make a comparison with a baseline or to a sustainable result [74]. An indicator for the sustainability assessment of manufacturing process functions to indicate the behavior of a unit process towards the triple bottom line—environmental, economic, and societal. Hence, the indicators which are used in the sustainability assessment of manufacturing processes are more likely to be performance indicators since the objective of the assessment is to improve the sustainability characteristic of an existing system. These indicators mainly fall into two classes [73,75]: (1) the abstract indicators, which do not have any kind of unit of measures and may be multi-layered to interpret the hierarchy relationships; and (2) the concrete indicators, which are quantifiable and directly put into practice to create the absolute value to the abstract indicators.

To specify which indicators should be selected and how to analyze them to evaluate a sustainable manufacturing process pose always challenges to researchers and practitioners in various manufacturing industries. There are many sustainability indicators that are publicly available to assess the sustainability performance of manufacturing processes. The contribution of this study also entails the establishment of an indicator set to assess the sustainability performance of manufacturing processes, as shown in Figure 4. This sustainability indicator set, which is mainly based on six major abstract indicators of sustainable manufacturing processes (see Figure 3), includes concrete indicators that have been effectively applied in the context. It can be helpful in the indicators' selection process.

In addition, an eDPSIR (enhanced driving force–pressure–state–impact–response) framework, which was developed by Niemeijer and de Groot [75] to select ecological indicator sets, is proposed. It can function to identify the required indicators which are not available in the literature for the assessment, considering inter-relations of indicators using causal networks rather than causal chains. In a nutshell, the eDPSIR framework simplifies the process of identifying key sets of indicators required for monitoring sustainability performance in a more consistent manner for complex manufacturing processes, such as sheet metalworking.

3.2.2. Desired Sustainable Level for the Selected Concrete Indicators: Potentials to Decrease

Jawahir et al. [25] mentioned that it is not possible to achieve the best levels of each indicator due to cost and technological implications as well as the proliferation of strong interaction among them, which often requires a trade-off. In this regard, what can be achieved are the optimized conditions with a minimal impact on the triple bottom line through sustainability-driven innovations on the existing manufacturing processes. Defining the desired level for each indicator establishes the direction of the sustainability assessment that the affected industries ultimately need to achieve—in other words, it is the assessment goal that ensures a shift from the unsustainable status quo to a more sustainable-based state. As reported by Moldavska and Welo [6], there are a number of papers that include potentials to decrease in developing sustainable manufacturing, employing the terms 'reduction' (such as the reduction in emissions), 'the desired level' (such as without emissions), 'formulations' that are considered as a guide in practice (such as minimize resource consumption or utilize minimum resources), and 'phrases' that are vague (such as smartly use natural resources or optimized use of resources). Therefore, the desired sustainable level for the selected concrete indicators should be distinguished to decrease the potentials. For instance, the quantity of cutting can be minimized by adjusting the cutting process parameters while maintaining the product quality aspect.

3.3. Step 3: Applying the Suitable Measuring Methods for Quantifying Each Indicator Involved in the Sustainability Assessment

3.3.1. Deterministic and Non-Deterministic Indicators and their Measurement Methods

Although the use of deterministic indicators is often preferred to be modeled using analytical and numerical methods, there are also the non-deterministic (uncertain/fuzzy) indicators that should be measured through apt means, such as fuzzy logic [7,25,31]. Among six major factors affecting sustainable manufacturing processes (see Figure 3), it is found that the manufacturing cost, energy consumption, and waste management are deterministic abstract indicators, and the environmental impact, personnel health, and operator safety are non-deterministic abstract indicators.

Classifying each indicator into deterministic and non-deterministic groups contributes to applying the right measurement methods for quantifying each indicator involved in the sustainability assessment. The work of Granados et al. [39], which was in pursuit of Wanigarathne et al.'s [27] research, can be exemplified for this matter. They have developed a quantitative model for the sustainability assessment of machining processes, normalizing the measurements according to the best/worst scenarios, and aggregating them with equal weight. However, it is not our objective to discuss the applicability of existing methods that could assist in measuring some of the selected indicators. Rather, we would like to point out that such methods exist; there are numerous references presented in Figure 4, which can be fruitful to exploit some of those methods.

3.3.2. Data Collection and Analysis

The next stage is to apply the right set of tools and techniques and collect the measurement data for the sake of the sustainability assessment. Some deterministic concrete indicators can be measured using types of machinery, e.g., power meter indicates the amount of electricity consumed by the machine throughout the operational time interval. Thus, it can be used to measure the power consumption of a machine utilized to do a certain process. The measurement in this data type is more straightforward as the researchers and practitioners can rely on existing analytical and numerical methods to analyze them [32]. For non-deterministic concrete indicators, such as the employees' health and safety that are deemed as crucial factors in capturing the societal sustainability performance of a production line [10], the measurement is associated with uncertainty and requires historical data analysis or surveys which are based on subjective judgments and experience. The measurement results obtained from the analyses must be able to give indications of the manufacturing process performance to assess if it approaches the desired levels that are being defined in the earlier steps. According to Joung et al. [32], the analysis of data impacts directly on making the final decision; an analytically-rich assessment can result in reaching effective managerial decisions towards developing sustainability in the manufacturing processes.

3.4. Step 4: Sustainability Performance Report

The final step of the framework is to compile the date of the assessment and document the sustainability performance report for the affected manufacturing processes. To be more exact, it encompasses the statement of the objectives and scope, administrative data, contextual information, and measurement results [32]. It is also crucial for the decision-makers to report if new technologies need to be invested in the existing processes for attaining a more sustainable situation. This will stimulate new sustainability-driven innovations within the company for improving the current situation through various process optimizations that do not require any major change or a large amount of investment. Moreover, the effects of developments in the manufacturer's sustainability should be reported for prioritizing managerial focus and making effective decisions on how to develop sustainable manufacturing processes. The report can be further expanded as far as the assessment covers all business sustainability activities.

4. Conclusions and Future Research Directions

After the seminal report "Our Common Future" as a normative reference, the manufacturing sector has significantly evolved unprecedentedly over the years, unanimously accepting that being sustainable is more beneficial. These sectors are the major contributors to our common future; many manufacturing processes consume excessive scarce resources and produce dangerous wastes and emissions. Due to these environmental concerns and the operational and societal challenges related to the existing risks to the employees' health and safety as well as the compliance with governmental environmental and societal regulations, it is evident that the manufacturing processes need to design and develop strategic frameworks to assess their sustainability performance.

Despite efforts to develop sustainability assessment frameworks for manufacturing processes, there has yet been any substantial inquiry into its establishment in sheet metalworking industries. As one of the preliminary studies, this research aims to address this shortfall, presenting a framework for assessing the sustainability of sheet metalworking processes with a clear boundary and explaining how each step performs by being broken down into stages. The contribution of this paper also entails the establishment of a sustainability indicator set to measure the sustainability performance of manufacturing processes; a set that is based on six major abstract indicators of sustainable manufacturing processes and includes the concrete indicators that have effectively been applied by previous researchers towards fulfilling the triple bottom line requirements in context. It can be helpful in the indicators' selection procedure to measure the sustainability performance of manufacturing processes.

This ongoing study has been subjected to the limitations that recommend directions to further research. The proposed framework in this paper was built upon two important processes—the cutting operations with a CNC turret punch press machine and sheet metal bending operations with a CNC press brake machine. Thus, further investigations can concentrate on validating this framework in another context not only to improve the sustainability performance of these two operations but also other types of sheet metalworking processes. The sheet metalworking industries, which are regarded as one of the biggest industries in the sectors of fabricated metal products, possess very little knowledge in the area of sustainability despite having served as sub-contractors to various industrial sectors. To advance this subject and come up with apt indicators that were poorly addressed, innovative studies are also needed to reflect the life cycle inventory databases and analyze data on the machine tool infrastructure and/or potential wastages and emissions which are scarce.

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