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A computer-aided unit process sustainable modelling for manufacturing processes: case for extrusion process

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ABSTRACT

Sustainable manufacturing assessment is meant to ensure that products are manufactured such that negative environmental impacts are reduced by conserving energy and managing the use of natural resources as well as ensuring economical soundness for the process. The main objective of this work is to introduce sustainable development methodology/models for manufacturing processes. For this purpose, the paper utilizes background data, develops a computer model and presents detailed case studies. This paper will identify and adopt key performance indicators (KPIs) and utilize these to assess the sustainability of extrusion process and their designs. Different manufacturing parameters such as material types, product specifications and manufacturing tools are considered in the process of measuring sustainability. The proposed computer model is verified with data obtain from actual aluminium extrusion plants.

ARTICLE HISTORY

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KEYWORDS

Sustainable manufacturing assessment; key performance indicator; extrusion process; energy; evaluation

1. Introduction

Manufacturing is the production of different products for use or sale using different types of machines, tools, chemical, manpower and biological processing, or formulation. Manufacturing processes manipulate such geometrical characteristics as shape, size, surface quality and accuracy as well as the physical and chemical properties of the intended product. A manufacturing operation consists of a combination of various unit processes each of which is controlled by both input as well as output information related to a given product. On one hand, input modules may refer to related to the machines, materials and various types of energy that is required to operate the machinery. On the other hand, the output modules are the finished product along with several types of wastages. The output characteristics of the final product are impacted by features of each unit process along with the employed sequence of machines (Gungor & Gupta, 1999).

For the optimization of a given unit process, proper control of process parameters, such as energy consumption, scrap produce, various types of cost is essential. In addition, customer satisfaction and healthy environment for workers also vary the outcomes of each unit process.

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1.1. Sustainable manufacturing

According to the United State Department of Commerce, sustainable manufacturing is defined as *'the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound'* (US Department of Commerce, 2009). The concepts of sustainability in manufacturing are generally fairly broad in scope and vary with process and product.

Sustainable manufacturing plays a vital role in the manufacturing of economic, social and environmental friendly products. For sustainable development of products, factors such as energy consumption, material wastage, gas emissions and use of non-renewable resources is to be targeted (Seow & Rahimifard, 2011).

1.2. Background of manufacturing industries

Every manufacturing industry has always impacted the environment and will continue doing so in one way or another, demanding an ongoing research effort to identify adoptable sustainable approaches. The ability to measure and assess the level of sustainability of a given manufacturing process will result in improving manufacturing processes and creating opportunities to benchmark performance of various manufacturing enterprises. For the purpose of building a proper sustainability indicator, a framework is developed in this paper based on the following steps;

- A proper system is defined with clear boundaries to help analyse and classify manufacturing processes.
- The process input, output, emissions, energy and other auxiliary elements are properly analysed where the machining parameters, working conditions and characteristics are considered.
- The indicators selected are measurable. Proper assessing tools are used and tests or experiments are performed for each pre-selected indicators to quantify the indicators measured.
- The results obtained from the proposed system are compared with real data from manufacturing plants for further improvement and fine tuning.

1.3. Sustainability indicators

A sustainability indicator is a single parameter employed to measure the condition of a sustainability aspect, such as material wastage or energy use (Jayal, Badurdeen, Dillon Jr, & Jawahir, 2010). Sustainability indicators help measure and assess sustainability and provide basis for improvement. Working to improve an objective requires an ongoing monitoring of its status, progress made towards realizing that objective and the issues encountered while achieving the set goals. Indicators are what one needs to help identify process objectives. Sustainability indicators help measure and assess sustainability and provide a basis for its improvement. There are numerous indicators which could be used as basis for sustainability assessment. Most commonly used indicators are: environmental, economic and social indicators.

The work in this paper aims at developing a roadmap for continuous improvement in the environmental sustainability performance of manufacturing companies. To develop more sustainable societies, industry needs to better understand how to respond to environmental challenges. Our motive is to develop a framework and tools that accelerate the transition towards a sustainable future. For the present study, we consider following environmental indicators.

- Electricity consumption
- Fuel consumption
- Co_2 Emission
- Solid wastage

Whilst the focus in this paper is environmental sustainability, future publications will report work in which the economic and social indicators will be considered. The formulation used to calculate sustainability indicators and equipment used to measure these parameters are explained in section 3.

2. Literature review

This section reviews related work on sustainability assessment and environmental issues in the manufacturing industry. A few papers on energy and material usages in different manufacturing processes can be pointed out. The literature survey is summarized by the following table

Besides comprehending and differentiating the scopes of papers presented by various authors, the literature review sought to assimilate and compare proposed methods, evaluate their strengths and weaknesses and identify research gaps (Singh & Sultan, 2017).

2.1. Research gaps

- Most of the research work has been done for the machining operations such as turning and milling while a limited study is done on primary processes such as extrusion process.
- Some studies proposed a system for energy estimation for extrusion process but energy use can change from one process plan to the other and this has not been considered previously.
- Sustainability data of energy and material flow analysis of manufacturing processes, including aluminium extrusion are lacking.
- A well-designed computer-aided approach would help to generate better sustainability for aluminium extrusion processes.

2.2. Research objectives

This research work has the following objectives:

Table 1. A comparative summary of the previous work.

No.	Details	Objective	Approach	Limitation
1.	(Zhang, Zhu, Li, Yaman, & Roy, 2015)	Develop models to gather information related to the sustainable manufacturing with the product design information.	Determines manufacturing process specific sustainability information, such as energy Represents the sustainability information with the help of information model Facilitates use of process information model sustainability data for product design for assessment	Does not support a science-based sustainability determination for manufacturing.
2.	(Elita & Annike, 2015)	Proposes a set of Key Performance Indicators (KPIs) for evaluating the sustainable manufacturing for cement industry based on the triple bottom line.	Identifies the initial key performance indicators (KPIs) for sustainable manufacturing evaluation. The initial KPIs are then validated to industry practices. Applies the Analytical Hierarchy Process (AHP) method is to prioritize the performance indicators by summarizing the opinions of experts	This work only includes opinions-based methodology for sustainable manufacturing
3.	(Lee, Kang, & Noh, 2014)	A model has been introduced for life cycle sustainability evaluation.	Suggests the essential requirements for evaluating the sustainability performance of manufacturing industry. Generates a sustainability model using a theoretical foundation comprising 20 principles Key performance indicators identified on the basis of principles, Manufacturing Sustainability Index (MSI) introducing the KPIs, an evaluation method and information management method.	Collection of data from shop floor and this data collection takes a long time
4.	(Madan, Mani, Lee, & Lyons, 2014)	Develop the needed measurement science, standards and methodologies to evaluate and improve sustainability of manufacturing processes.	Develops standard reference sustainability characterization methodologies for unit manufacturing processes focusing on injection moulding. Calculate theoretical energy by considering different parameters of injection moulding process.	Only energy evaluation and improvement indicators are identified
5.	(Lee et al., 2014)	This paper suggests a simulation based analysis for sustainable manufacturing.	Defines sustainability input/output factors and constructs a framework for simulation based analysis of sustainability. Generates a model using sustainability factors and P3R information. Assigns sustainability factors to the existing each unit process with the relation of routing information	This work does not include science-based measurements of sustainable manufacturing

(*Continued*)

Table 1. (Continued).

6.	(Seow & Rahimifard, 2011)	This work presents a novel modelling framework to represent the total energy required to manufacture a unit product.	Investigates the combination of energy used both at the plant and process levels. Represents the amount of energy attributed for a unit manufacturing process. Proposes a framework for modelling embodied product energy (EPE) during manufacturing.	Only energy-related indicators are identified
7.	(Kim, Shin, Shao, & Brodsky, 2015)	Propose a decision guidance framework to address the limitations of LCA methods	Introduces a decision guidance framework which consists of six phases for sustainable analysis of product. Goal and scope definition Data collection Model generation for processes Sustainability performance analysis Interpretation Decision support and guidance	Only energy and emissions related indicators are identified
8.	(Kellens, Dewulf, Overcash, Hauschild, & Duflou, 2011a)	Propose a life-cycle analysis (LCA) oriented methodology for systematic inventory analysis of the use phase of manufacturing unit processes providing unit process datasets to be used in life-cycle inventory (LCI) databases and libraries.	Develops the methodology as a framework of the Co_2PE comprising two approaches with different levels of detail. Consider energy, material, power and time studies to evaluate life cycle inventory analysis for machining processes.	A large amount of LCI data are required for each process
9.	(Kellens, Dewulf, Overcash, Hauschildl, & Duflou, 2011b)	Demonstrating the application of life cycle assessment oriented methodology for systematic inventory analysis of machine tool.	Generates uniform, complete and robust LCI datasets of the machine tool use phase of unit manufacturing processes	A large amount of LCI data is required for each process
10.	(Jayal et al., 2010)	Present an overview of new concepts that are emerging for evaluating sustainability contents at the product, process and system levels for enabling sustainable manufacturing.	Proposes sustainability scoring methods for products and processes Predictive models and optimization techniques for sustainable manufacturing processes. Focusing on dry, near-dry and cryogenic machining as examples	There has been lack of metrics to quantity the extent of environmental and social impacts

- Identify the most suitable KPIs to measure the environmental impact of the extrusion process.
- To develop a framework which evaluates different sustainability indicators and provides sustainability comparison at different sub processes levels for the extrusion process.

In order to achieve the objective of present work, a sustainable manufacturing assessment methodology is adopted. The study begins with the raw material processing, process input/outputs and unit manufacturing processes evaluation and extends up to data collection and validation.

The aim of this study is to help improve the sustainability aspects of a manufacturing process taking place on a company premises. Pre-processing of raw material production and the use of the product outside of the company is not considered within the scope of the study. In the study, energy consumption is taken into consideration as well as off-site air emissions specifically emissions related from the production of energy and on-site air emissions from the burning of fossil fuels (Thirez & Gutowski, 2016). Waste of processing material within the company is also within the scope of the study yet transportation of raw materials and capital equipment has not been considered in this study. System boundaries for aluminium extrusion plant are shown in Figure 1.

The system boundaries include emissions from such sources as furnace oil, diesel oil, electricity and solid waste. Waste water emissions have also been included in the industrial waste. The amount of electrical energy consumed is calculated in kilowatt-hours (kWh), fuel consumption will be given in litres for oil-fired furnaces but solid waste will be calculated in kg.

3. Mathematical evaluation of sustainability indicators

The methodology to evaluate sustainability indicators, namely, electrical energy, solid wastage, Co_2 emission and fuel consumption is discussed in the below paragraphs.

3.1. Energy use indicator

For energy indicator, electrical and fossil fuel energy is used. The following expressions are used to calculate energy in any manufacturing process.

3.1.1. Electrical energy

Electric energy consumption and fossil fuel consumption can be calculated by using theoretical and actual measurement formulations. Therefore, theoretical rated energy consumption, E_r, can be calculated by the following equation;

$$E_r = P_r \times t \tag{1}$$

where P_r is the rated power (kW) of a given machine and t (hours) is the time used to achieve a specific task on that machine. Electrical energy in equation (1) is reported in kilowatt-hours (kWh).

Actual energy use, E, for manufacturing process is measured for different equipment during the actual manufacturing process. This energy consumption is determined by measuring the actual values of current, I, voltage, V, and time taken from the actual measured data. The below formulation provide value of actual energy consumption.

$$E = \sqrt{3} \times V \times I \times t \times \cos\varphi \tag{2}$$

where φ is the phase angle.

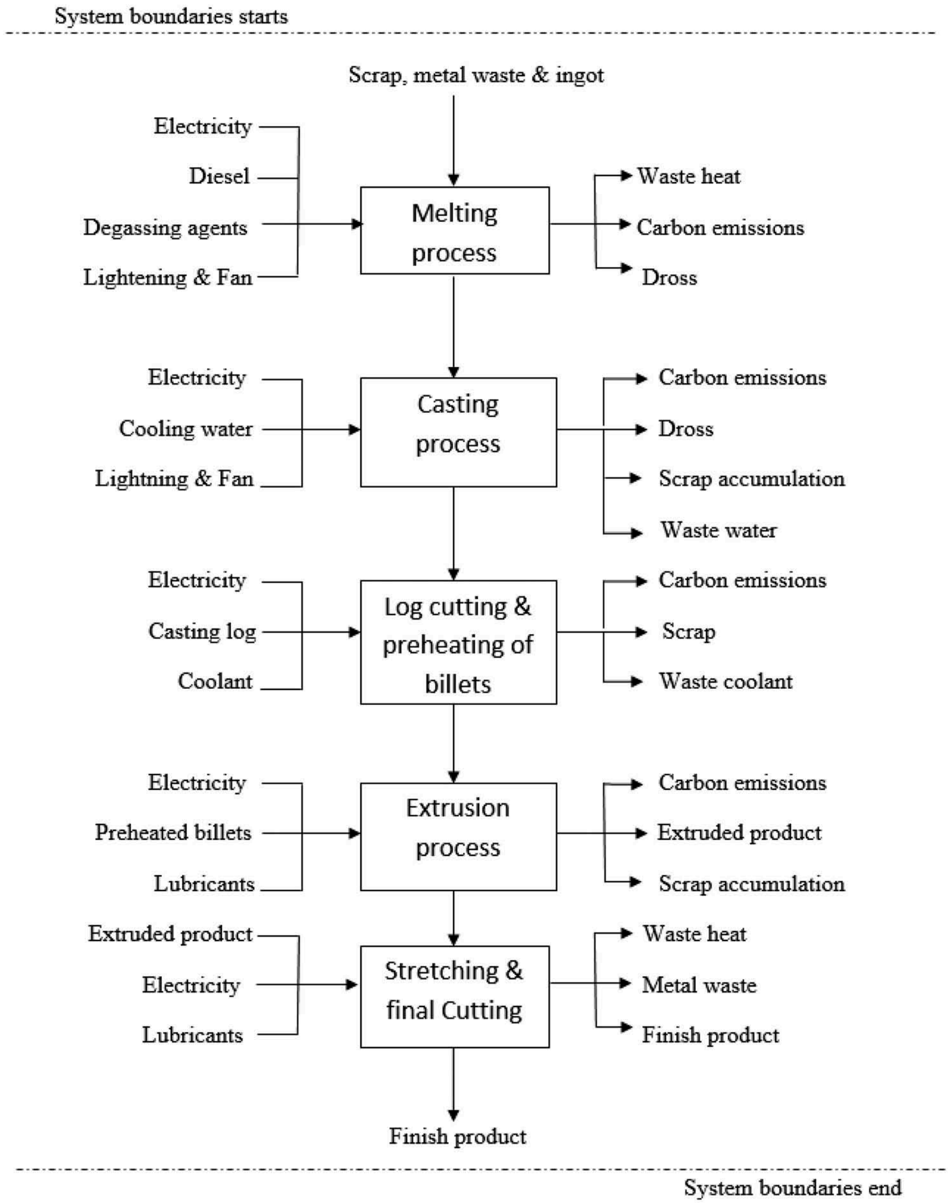

Figure 1. Input/output diagram of an aluminium extrusion plant.

3.1.2. Quantity of fuel consumption

In the process of melting metal in oil fired furnaces, heat energy is provided in form of furnace oil, diesel and other fuels. The quantity of fuel consumption primarily depends on the heat energy required to increase the temperature of material from the ambient temperature to the required injection temperature. The process of melting features a complex phase transformation and change in state of material from solid state to the liquid. During this transformation, heat energy is required to raise the temperature of the casting alloy from ambient to superheated and melting temperatures. Thus, total heat energy can be given by the following relation (Bill, 2005).

$$Q_s = MC_s(T_s - T_a) \tag{3}$$

$$Q_f = M\left(C_s\ (T_1 - T_s) + H_f\right) \tag{4}$$

$$Q_{sh} = MC_s\ (T_{sh} - T_1) \tag{5}$$

$$Q_t = Q_s + Q_f + Q_{sh} \tag{6}$$

where,

- M= Mass of metal in the furnace;
- C_s = Specific heat of the metal;
- T_a = ambient temperature;
- T_s = Temperature at the liquid state;
- T_1 = Temperature at the moulding state
- Q_s = Heat to raise temperature from room temperature to start of melting
- Q_t = Total heat required for the melting process
- Q_f = Heat required to increase casting alloy from the solidus to liquid temperature
- Q_{sh} = Heat required to super heat casting alloy to holding furnace temperature
- H_f = Latent heat of fusion of alloy
- T_{sh} = Temperature at the saturation heat state

By knowing such parameters as the mass of metal processed, temperature at each process total heat required in melting can be calculated.

The quantity of fuel needed for the melting process depends upon a number of such parameters as the type of material, melting temperature and mass of material. An estimate for the volume, V_f, of fuel required can be calculated from the following equation,

$$V_f = \frac{Q_t}{\eta \times H_f \times \rho_f} \tag{7}$$

where

- V_f= The fuel volume flow rate required;
- H_f = Heat value of fuel per unit mass;
- ρ_f = Fuel density
- η = Efficiency of the furnace

The actual amount of fuel used is also measured and compared with the estimated value.

3.1.3. Air emissions

Emissions have a particular significance due to their harmful effects on the environment. Co_2 emission into atmosphere is caused by electrical energy and fuel consumption which occurs in any manufacturing process. Air emissions occur due to electrical energy depends upon the consumption of electricity. The below expression provides an estimate for air emission which results from the production of electrical energy.

$$C_w = E \times f \tag{8}$$

where f is a factor used to estimate Co_2 emission as provided by Electricity Authorities in various locations. For example, for the Northern Grid this factor is 0.84 tonne of Co_2 per MWh of electricity used. (Jeswiet & Kara, 2008). Some authorities provide the factor f in form of tonnes of CO2 per unit volume of the fuel consumption instead of unit energy produced. For example, according to the US Environmental Protection Agency, emission factor for diesel is 2.63 kg of Co_2/litre of burned fuel. If this case, CO2 emitted to atmosphere would be given as follows;

$$C_w = V_f \times f \tag{9}$$

3.1.4. Solid waste

The major material wastage occurs during the heating process which contains transformation of material from solid to liquid. Material losses depend upon a number of factors such as, type of furnace, type of fuel and material characterization. Melting loss estimates for furnaces can be taken from the data provided by the Cast Metal Coalition. Generally, melting furnace are expected to exhibit a material loss that ranges from 0.75% to 1.25% of the initial furnace load. As such, the solid waste equation for extrusion process can be expressed as follows;

$$Solid\ waste = M_{Molten\ metal} \times (\%of\ metal\ loss) \tag{10}$$

Solid wastage is usually calculated in kg per work shift.

4. Matlab model to evaluate sustainability for extrusion process

A model has been constructed to quantify the sustainability characteristics of the extrusion process and its allied sub processes. The model, which is coded in a computer package, is so comprehensive it takes into account the parameters of various production tools, the materials involved, the fuels employed and the produced part. The proposed model contains various coded modules employed to enter and process of data by the mean of mathematical calculations and provide end results in the form of bar charts and graphs. The user interface for the model is depicted in Figure 2.

The computer aided approach used in this paper is designed to be user friendly. The first step is to select the manufacturing processes class along with major unit process, such as extrusion or die-casting. Then materials and alloys are selected from provided databases.

The final step is to select the sub processes which are associated with major metal forming operations. For example, melting, billet heating, log cutting and final cutting are sub processes for extrusion process. The computer system presented in the paper can evaluate the sustainability of different sub processes as well as compare two sub processes.Figure 3 shows the system architecture of proposed system.

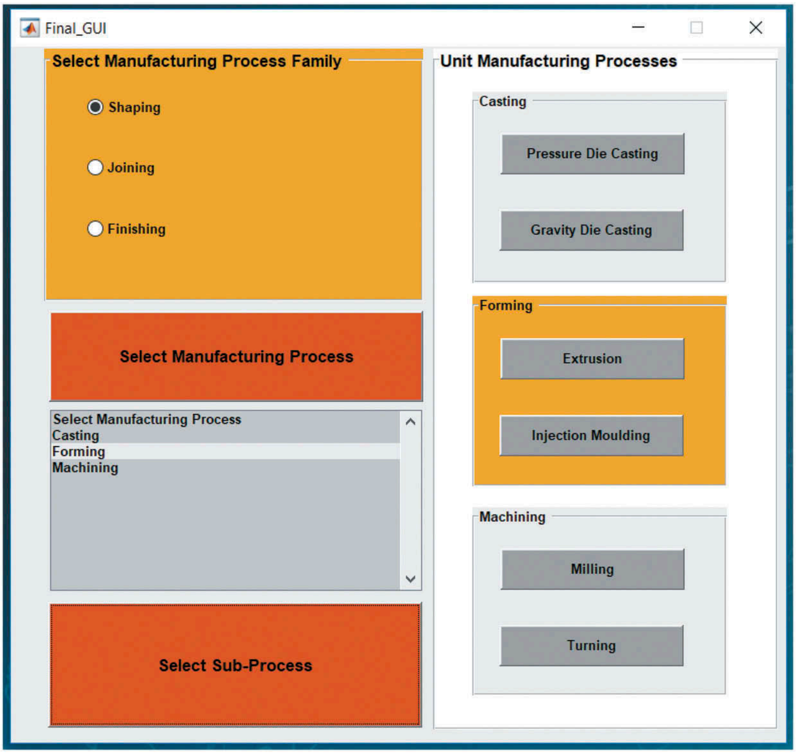

Figure 2. GUI for different manufacturing processes.

5. Case study

For the validation of proposed computer model, a case study of an extruded aluminium product is presented. The proposed system takes the required information such as mass of charge, time per cycle, melting, heating of billets and superheat temperature along with other process parameters. Table 2 offers some insight into the list of parameters used by the model for sustainability calculations. The system processes the input information for the determination of sustainability indices.

For the mathematical modelling, the system employs various documented properties of material, alloys, furnaces, machine databases and theoretical formulae coded into the system for the determination of sustainability. Results of the sustainability analyser for the extrusion process are shown in Figure 4.

The proposed system utilizes theoretical formulae for the determination of indicators. To check the accuracy of the sustainability analyser, the system results have been compared with the actual measured data obtained from an aluminium extrusion. Table 3 shows the actual results and output material for aluminium extrusion, where the sustainability analysis is performed per shift basis. The calculated sustainability indices are shown in Figure 5.

Figure (5a) of sustainability indices represents Co_2 emissions occurred during the aluminium extrusion process. Figure (5b) and Figure (5c) indicate the energy used in

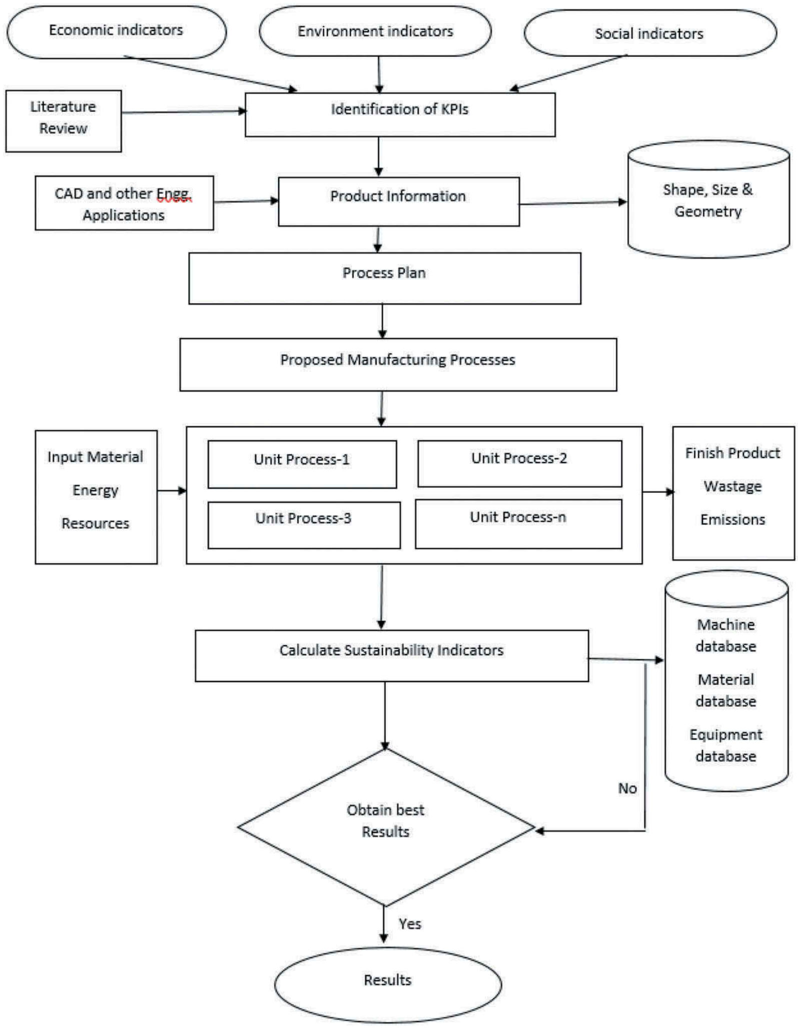

Figure 3. System architecture of the Sustainability Assessor.

form of electrical and fossil fuel energy, respectively. Figure (5d) represents the solid waste produced during the extrusion process.

6. Results and discussions

To assert the accuracy and validity of the proposed model, a comparison between the actual measured data and the results obtained by the proposed model has been conducted with the aid of Figure 6. Deviation in the values of sustainability indicators obtained by the proposed model as compared to actual data are also listed in Table 4.

The values listed in Table 4 reveal that the calculated estimate of carbon emission is only 1.2% more than the corresponding data obtained by actual measurements. This minor deviation can be attributed to using catalogued values for rated power of

Table 2. Parameters of the sustainably model for extrusion Process.

S.No	Sub-processes	Inputs parameters
1.	Metal process	• Melting furnace parameters • Material mass • Time for melting • Furnace efficiency • Initial temperature • Final temperature
2.	Casting and transportation	• Cycle time for tilting motor • Cycle time for water inlet motor • Cycle time for water outlet motor • Cycle time for lifting motor • Cycle time for cooling fan • Casting charge
3.	Log cutting and preheating of billets	• Cycle time for log cutting • Cycle time for heating billets • Heater efficiency • Ambient temperature • Final temperature • Total mass of casting logs
4.	Extrusion and rough cutting	• Cycle time for extrusion process • Cycle time for rough cutting • Extrusion metal input
5.	Stretching and final cutting	• Cycle time for stretching process • Cycle time for finish cutting • Total metal input

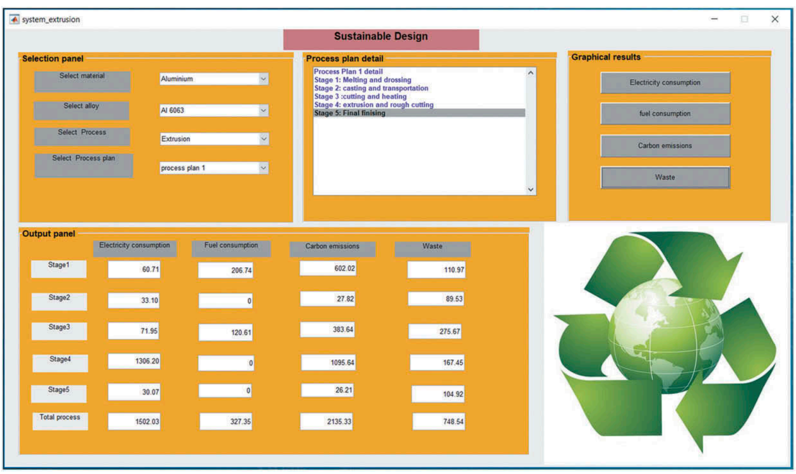

Figure 4. Sustainability analyses for extrusion process.

various equipment in the calculations. In reality, however, the actual power consumed by a machine is expected to vary slightly based on operating conditions. The use of rated power values also resulted in estimating the energy consumption to be 4.9 % higher than what the actual data suggested as shown in Table 4.

Fossil fuel consumption, which has been calculated from the actual measured data, is more than the proposed model estimated. This variation is due to energy losses which take place in real situations but cannot be reliably considered in theoretical calculations. In fact, the actual data suggested 5.85% higher fuel consumption than what the model estimated. The solid waste estimation part of the proposed model produced results

Table 3. Actual energy used and output materials.

Sub process	Input Metal (kg)	Electricity consume (kWh)	Fuel consume (litres)	Carbon emission (kgCO2)	Solid wastage (kg)	Output metal (kg)
Melting & drossing	3264	48.18	213	600.66	115	3149
Casting & transportation	3149	31.54	0	26.49	92	3057
Log cutting & preheating of billets	3057	68.42	128	394.11	288.9	2770
Extrusion & rough cutting	2770	1241.05	0	1042.48	172	2598
Stretching & final cutting	2598	28.56	0	23.99	1055	24,895
TOTAL	-	1417.75	341	2087.73	776.4	-

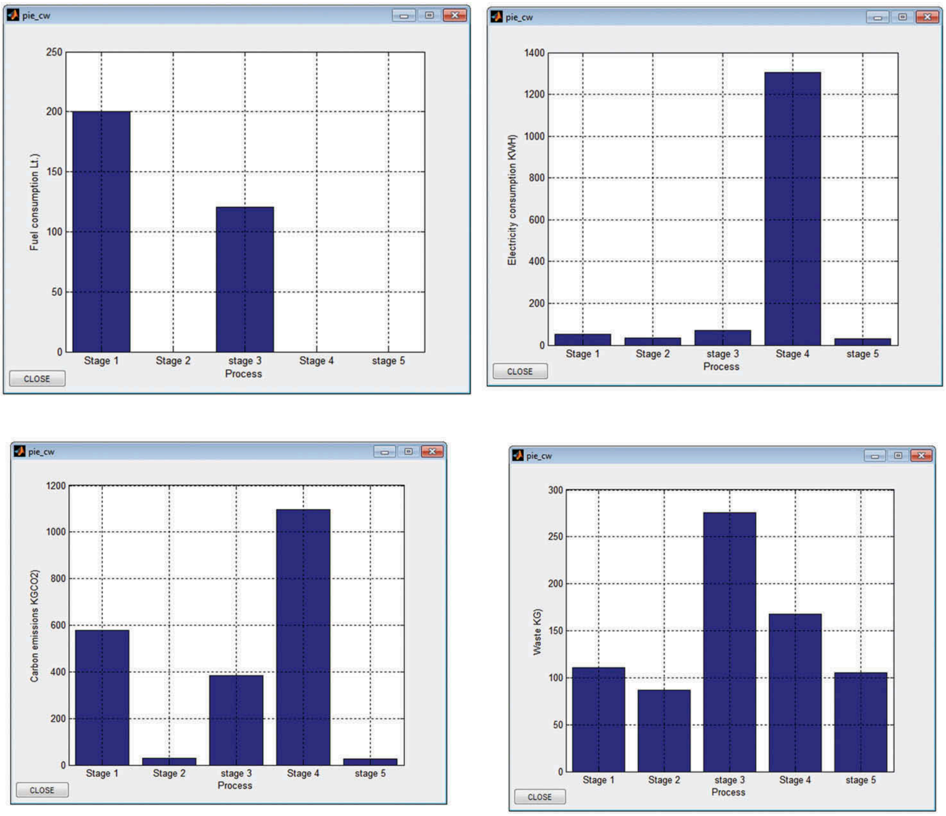

Figure 5. Sustainability indices evaluation at every stage of extrusion process. (a). Co_2 emissions. (b). Electrical energy used. (c). Fossil fuel used. (d). Solid waste.

which are 3.9% out when compared to the actual data. In actual practice, the solid waste generation was higher than the theoretical estimate. This outcome is expected to vary with data collected from various extrusion plants.

Overall, the presented model demonstrates levels of accuracy which qualify it for the use as a design tool for future manufacturing processes in order to ensure that a sustainable outcome will be achieved.

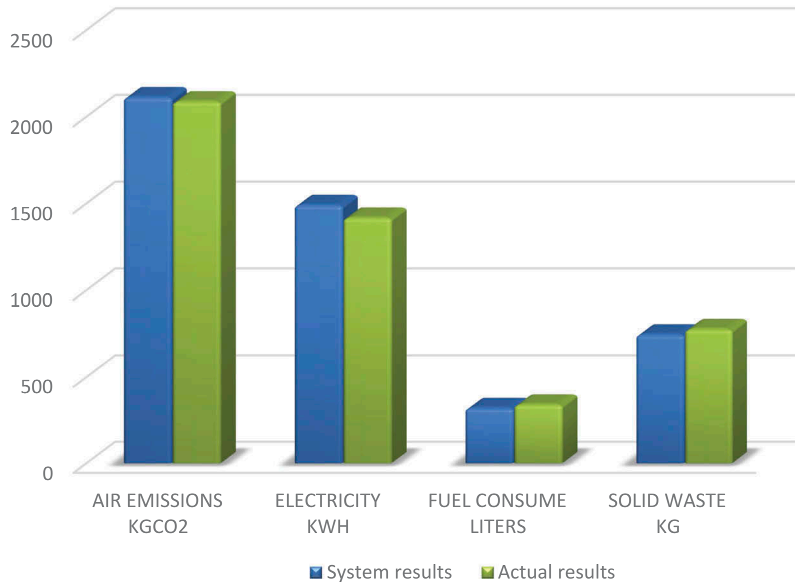

Figure 6. Comparison of system results with the actual measured industrial data.

Table 4. Percentage error for system results and actual results.

Indicators	System results	Actual results	% Error
Electricity	1502.03 kWh	1417.75 kWh	4.9
Co_2 emissions	2135.33 $kgCo_2$	2087.73 $kgCo_2$	1.2
Fuel consumption	327.35 litres	341 litres	5.85
Solid waste	748.54 kg	776.4 kg	3.9

7. Conclusions

A framework for evaluating the sustainability of extrusion processes has been presented in this work. The system combines mathematical modelling with information available in industry databases for various parameters of manufacturing processes. The indicators used in this work are air emissions, energy use and solid waste. In the computer-aided model featured here, user can enter the input parameters or choose the value of process parameters from pre-stored. The process plan of a product is simulated in the produced system in order for accurate results to be obtained. The system processes the input data and produces the results in form of key performance indicators. The present system has the following advantages.

- The results determined by the system are close to that calculated based on actual measurements of process parameters.
- The results show that the percentage error for the system for electricity, Co_2 emission, fuel consumption and solid waste are 4.9%, 1.2%, 5.85% and 3.9%, respectively.
- The results show that proposed system is valid and could be used for calculating energy use, emissions and solid wastage in manufacturing companies.

- The proposed framework could also be used to measure progress of a company in terms of energy and material uses at various stages.

The future work includes extending the system utilization for whole life cycle for manufacturing processes considering economic and social indicators.

Findings

Sustainability stands on three pillars, economics, social and environmental. A sustainability measurement framework has been crafted in response to environmental and energy challenges.

Research limitations/implications

The focus in this work is on sustainable manufacturing and product development. This work will be extended in the future to cover the manufacturing sector at product, plant and process levels.

Practical implications

The proposed concept and models of the sustainability measurement framework is tested with real industrial case studies and data. The work will also rely on published sources for further information on sustainability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

A Snapshot of the GUI of different sub-processes for extrusion.

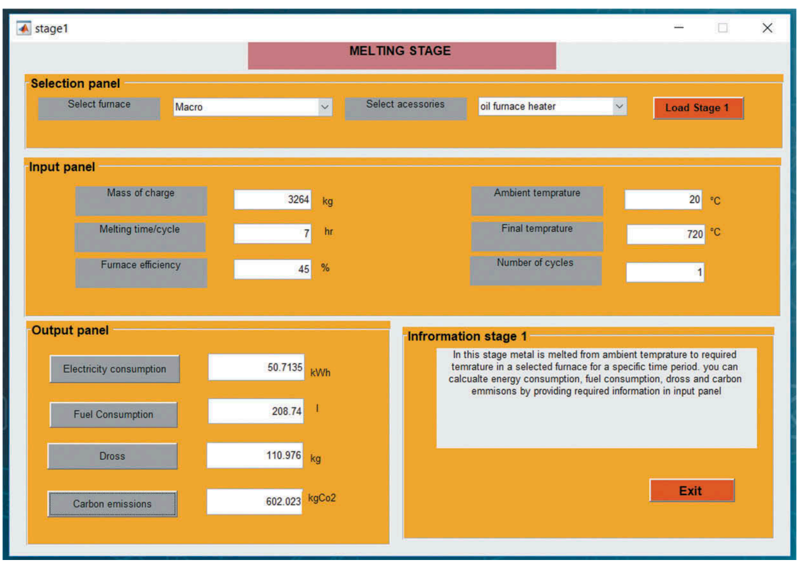

Figure A1. Sub-process form for melting stage.

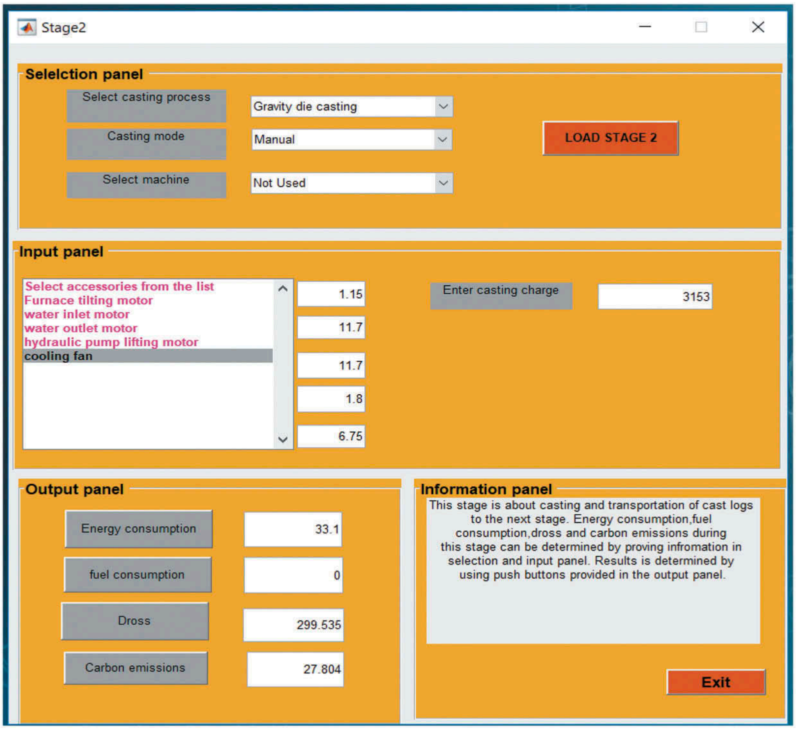

Figure A2. Sub-process form for casting process.

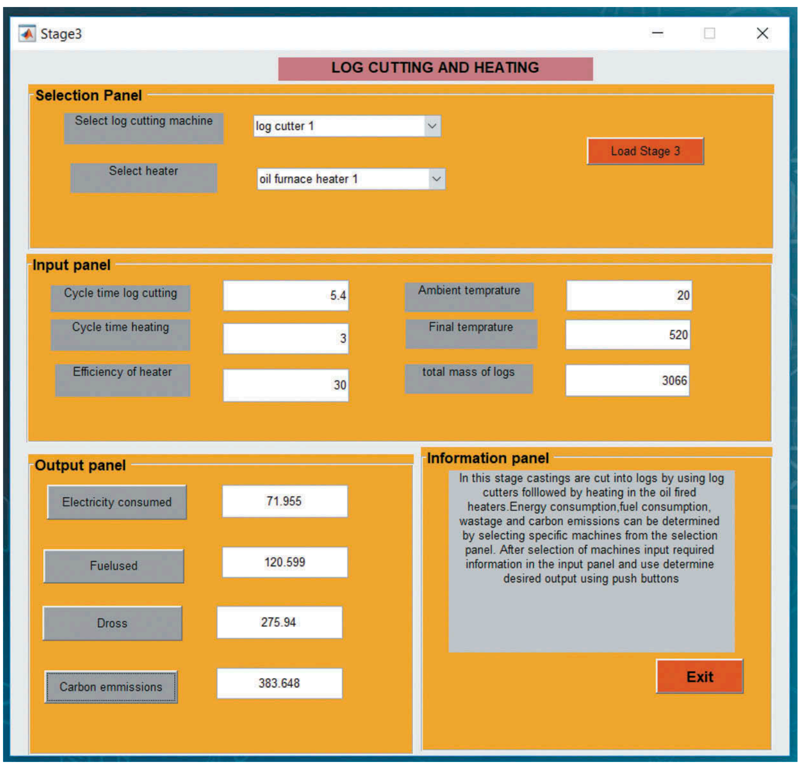

Figure A3. Sub-process form for log cutting & heating.

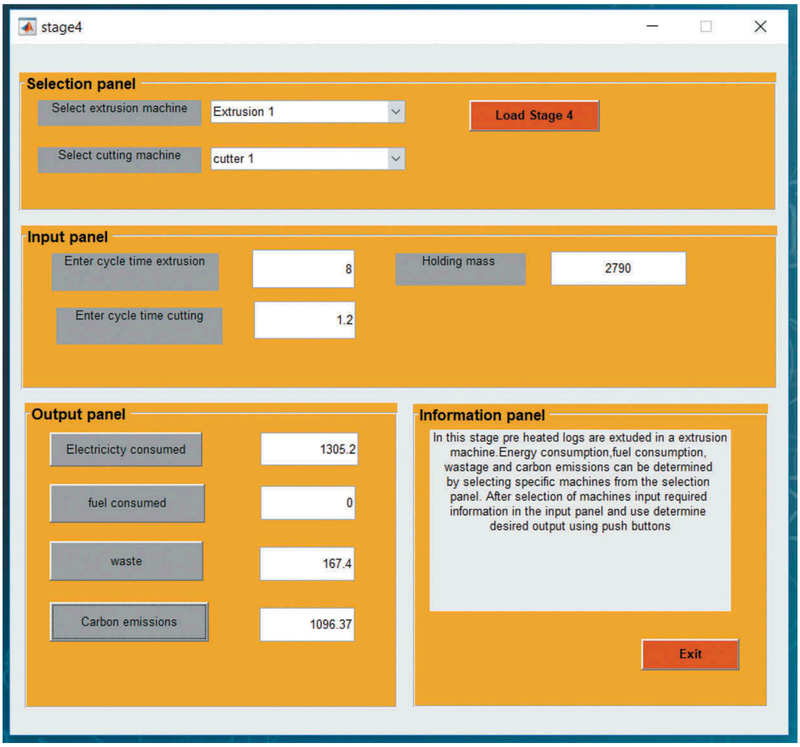

Figure A4. Sub-process form for extrusion process.

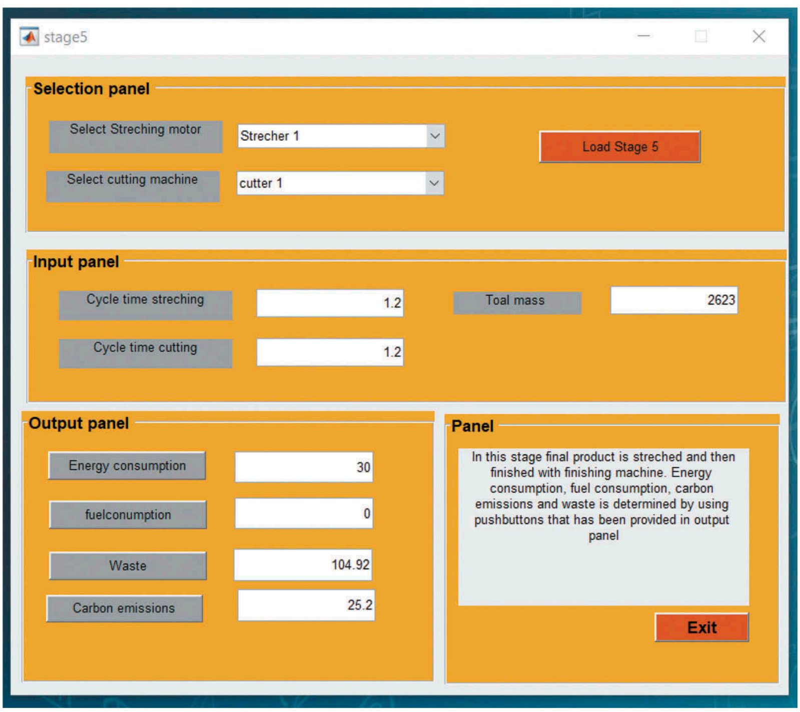

Figure A5. Sub-process form for stretching & final cutting.