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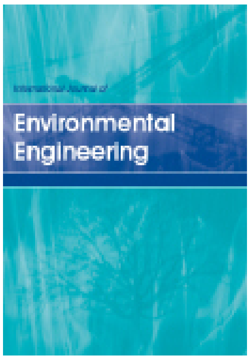

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Evolutionary design framework and assessment of the sustainable manufacturing systems

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Abstract: The need for sustainability in modern manufacturing systems is influenced by environmental-driven objectives including lower emissions, minimal utilisation of natural resources, reduced energy usage, etc. In this work, for developing green manufacturing systems, optimal improvement plan is implemented using recycling tool without affecting productivity. Using survey data based on recycled content, this paper empirically evaluates various environmental metrics affecting water management, climate change, air quality and greenhouse gas impact. In addition, we provide an estimate of net energy consumption and global average carbon emissions for different types of materials employed in manufacturing industry. The iterative execution of evolutionary genetic algorithm is implemented for minimising the greenhouse effect by considering the application of distinct selection, mutation and crossover operations. Moreover, simulation results demonstrate that the proposed design model outperforms the previous works in terms of reduced emissions by up to 86%, energy conservation by huge proportion of 247.2 and 72.86% lesser carbon footprint.

Keywords: genetic algorithms; green manufacturing; sustainable development; system simulation.

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1 Introduction

Recent manufacturing systems require sustainability as a key parameter for reducing negative environmental impacts and ideal consumption of limited energy and natural resources, whilst maintaining higher system productivity. Sustainability is a novel paradigm in manufacturing, since the organisations face diverse challenges to maintain their businesses and let the business to be endurable. With the evolving transition towards sustainable development in modern manufacturing industries during the past few decades, achieving long-term sustainability coupled with the environmental benefits has been a critical perspective for global marketing. Sustainable development principles adopted in manufacturing sector aim at achieving efficient resources utilisation and preservation of ecosystem coupled with controlled energy consumption (Ganda and Ngwakwe, 2014). Attaining sustainability with less energy consumption and reduced waste is an implementation objective for manufacturing products at the design stage. Sustainability can be defined as the development that meets the demand of present time without compromising the capability of future generations to meet their own needs, and without destroying the quality of the environment (Koltun, 2010). Sustainability can be achieved by mitigating the adverse impact of non-biodegradable raw materials on the environment. To reduce the manpower and energy requirements, the green revolution developmental initiative is adopted to support the long-term sustained economic growth. Specifically, the application of green revolution strategy in India was initiated in the 1960s to augment and improve the agricultural and economic productivity through the sustainable technology and agriculture research. Norman Borlaug regarded as the father of green revolution and modern agriculture for productivity growth, introduced the enhanced methods of cultivation. Achieving sustainability necessitates the development of a transformation process that enables individuals, communities and organisations to maintain the productivity through profitable products without adversely impacting the ecology. The primary focus of sustainable development in the manufacturing industry is the improved management of natural resources with constrained environmental impact through the utilisation of reusable and climate-friendly materials. From the industrial ecosystem perspective, the man-made ecological repercussions of sustainable manufacturing sector necessitates the zero-emission principle for promoting the innovation, productivity, resource efficacy and sustained growth. Recently, the Energy Conservation (Amendment) Act 2022 passed by the Parliament of India specifies a carbon credit trading scheme aimed at the curtailment of carbon emissions. This key standard for carbon reduction initiatives empowers the central government to ensure faster decarbonisation of the Indian economy.

In manufacturing systems, products should be designed in a way such that the customer needs are satisfied enforcing the implementation of the system. Moreover, the product development should ensure minimal environmental degradation and low cost of ownership aimed at facilitating economically affordable system. Sustainability in manufacturing process is executed with enforcement of the balanced growth for establishing a novel business model or implementing innovation in existing business models, i.e., the growth that encompasses the economical and social concerns, without damaging the environment. Key challenges that motivate towards the adoption of sustainable development by the manufacturing system can be broadly classified into three categories (Abdullahi and Abdullah, 2015; Mensah, 2019):

- Economical such as declined product life-cycle, product variety, rapid technology modifications owing to reduction in time of technological obsolescence, demand fluctuations due to increased standard of living, etc.
- Environmental such as climate change on account of greenhouse effect, depletion of natural resources of energy, etc.
- Societal such as non-availability of skilled manpower, aging workforce, etc.

The Organisation for Economic Cooperation and Development (OECD) is an international organisation with a mission to promote policies for improving the worldwide economic and societal well-being of individuals. It has provided several indicators demonstrating how sustainable the manufacturing system is. The presented work has employed these quantitative indicators for the analysis and improvement of environmental performance. Some of these metrics for sustainable manufacturing include the greenhouse gas emissions intensity and energy consumption intensity as a function of the percentage of product recyclability for different types of materials used in the production and distribution industry. In operations scheduling, the resources such as manpower (skilled labours), machines, tools, etc. are allocated over time horizon to perform a collection of tasks. Additionally, non-renewable minerals such as iron ore, rhodium, manganese, etc. owing to their finite production, are considered critical due to their high risk of maintenance, supply and economical impact. Moreover, these restrained resources exhibit crucial challenges in their extraction, processing and transportation, which subsequently consume energy and generate residuals. Therefore, the utilisation of these substances is restricted by law to attenuate the environmental loss imposed by their usage. In general, it refers to the context of environmental legislation and policy frameworks adopted to monitor and restrict environmentally hazardous practices throughout the world. For instance, the Kyoto protocol that enforced the United Nations Framework Convention on Climate Change is implemented to limit and alleviate the negative consequences of greenhouse gas emissions through national measures. In particular, the industrial production system is determined by the characteristics of the product chosen to be manufactured. Besides, the transformation process of inputs into outputs should be managed in a controlled way and made more sustainable by improving efficiency, reducing waste and alleviating the defects. For this, production planning is effectuated as a sequential top-down approach and implemented as a hierarchical process. The output generated by this mechanism can be tangible goods (or products) or intangible services provided to the end-consumer. In recycling, the form of the output is transformed and utilised as part of the input to other product manufacturing. The proposed study investigates the impact of recycling in reducing the environmental footprint of various types of products. Manufacturing goods from the existing recycled materials needs lower energy than devising them from new raw materials. In addition, this process facilitates the natural resource conservation, generation of lesser carbon emissions, and destructive climate change suspension.

Several drivers and motives for sustainable manufacturing design are discussed for the Web of Science and Google Scholar database from the organisational market perspective (Hariyani et al., 2023). Green innovation strategies for manufacturing sector are implemented through a hybrid technique comprising of fuzzy Delphi, interpretive structural design and cross-impact classification methods to achieve waste management and reduction of environmental pollution (Ullah et al., 2022). Work in Kannan et al. (2023) deploy multiple-criterion decision-making analysis tools to evaluate and further alleviate the conventional challenges posed by the sustainable manufacturing system, together with the contribution to the novel smart manufacturing and Industry 4.0 technological field. Furthermore, the genetic algorithm has emerged as a potential scheme for attaining the stochastic optimal solutions with the bounded computational complexity. Based on the fundamental operations of search and optimisation, this meta-heuristic learning approach iteratively searches the substantial feasible solution space with random execution to determine the global optimality. Inspired from the biological evolution of complex adaptive systems, genetic optimisation provide a well-established methodology for heuristically implementing the general nonlinear problem architecture. This system design and modelling framework incorporates the key issues of genetic encoding, learning of well-defined fitness functions, initialisation of population of individual solutions, and specification of the basic genetic operations, viz. natural selection, crossover, and probabilistic mutation functions. Optimal assessment of environmental sustainability can be determined through the step-wise genetic optimisation approach (Tambouratzis, 2016). A green transportation system based on genetic algorithm scheme is developed for the logistics service providers to optimally minimise the economic and environmental cost (Lin et al., 2014). Spatial optimisation model based on genetic algorithm is implemented to handle the environmental pollution and aging issues in urban planning conditions under feasible time constraints (Yoon and Lee, 2017). A mathematical cost model based on genetic algorithm is used to evaluate near-optimal solution for determining the impact of carbon emissions on the environment and diminishing the carbon footprint of renewable energy supply chains (Sadeghi and Haapala, 2019). These existing works for sustainable manufacturing based on genetic optimisation technique did not evaluate the reduction in greenhouse gas emissions generated through the industrial activities. However, the presented work employs the unconstrained optimisation system for minimising the overall greenhouse gas emissions intensity through the retrieval of the optimal fitness value, score histogram and selection function associated with the nonlinear augmented Lagrangian algorithm. In this work, the effect of appropriately choosing and implementation of various selection, mutation and crossover operations is considered to develop and simulate the proposed sustainability model for the improved ecological conditions.

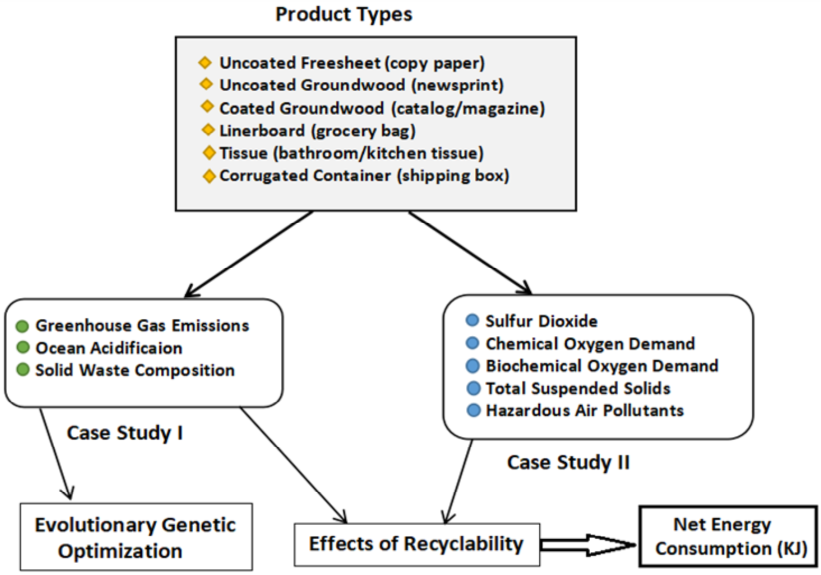
1.1 Objectives

The main objectives of the proposed manufacturing design model are listed as follows:

- This study is focused on the specific paper/wood-based products and the impact of recyclability on the environmental footprint. For this, two case studies are implemented to evaluate the influence of recycled content for different types of products on the eight significant ecology conservation parameters. Figure 1 shows the scientific hypotheses through the schematic representation for tentative design modelling of the proposed sustainability framework.

- In one case study, we study the repercussions of ocean acidification, greenhouse gas emissions and solid waste generated with the varying levels of product recycled content.
  1. The impact of ocean acidification parameter is crucial for the sustainable management, conservation and protection of aquatic and marine ecosystems.
  2. Reduction of greenhouse gas emissions is essential for climate change monitoring and global warming prevention.
  3. In addition, the solid waste management is firmly associated with the nutrition and resource assurance, sustained production and consumption, and societal health issues.
- In another case study, various metrics related to the ambient air quality and water conservation standards are employed including sulphur dioxide (SO_2), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), and hazardous air pollutants (HAP).
  1. The first criterion is connected with the controlled emissions of common air pollutant of SO_2 gas into the outdoor environment from the industrial processes for advancement towards more sustainable manufacturing practices.
  2. Next, the COD determining the degree of pollution in the water sample is a qualitative characteristic of the amount of organic substances found in the wastewater and surface water.
  3. Likewise, the BOD is the amount of oxygen required by the biological sources to decompose the organic content present in the waterbody over a certain period of time.
  4. Removal of the total solid particulate matter dissolved in water through sedimentation and filtering techniques is another objective to ensure the sustainability and evolution of water systems management.
  5. Moreover, the influence of toxic air pollutants on natural ecosystems is investigated to accomplish waste minimisation, pollution control, and mitigated respiratory and cardiovascular health risks in humans.
- The utilised scale of measurement for these diverse indicators is taken as pounds. Different types of manufacturing materials employed for the proposed study and sustainable analysis include the paper/wood-based products such as uncoated freesheet (copy paper), uncoated groundwood (newsprint), coated groundwood (catalogue/magazine), linerboard (grocery bag), bathroom/kitchen tissue, corrugated container (shipping box).
- Besides, the net energy consumption is computed for the varying proportion of the recycled content for different types of material usage.
- Furthermore, the iterative implementation of the evolutionary genetic optimisation technique is conducted for minimisation of the greenhouse effect influencing the global warming and climate change. For this, the application of three disparate combinations of selection, mutation and crossover operations are employed to compute their integrated effects on the environmental performance.

Figure 1 Schematic modelling of the proposed sustainable manufacturing system (see online version for colours)



1.2 Related work

The evolution of sustainability in product manufacturing has given rise to a substantial body of literature addressing the deployment of sustainable practices in the execution of business operations. Paul et al. (2014) resolved the issues of environmental management and sustainability in the context of automobile manufacturing processes and systems. In the development of this study, it was demonstrated that sustainable product design can be accomplished through wastage reduction and efficient energy usage. A survey of innovations and technologies in the field of green manufacturing has been presented as a potential solution to reduce the environmental impacts and improve the organisational performance (Sen et al., 2015). The location-based geographical information technique has been employed to characterise the green manufacturing operations in sustainable enterprises paradigm (Vadoudi et al., 2014). Sustainability analysis of semiconductor manufacturing industry is performed by implementing the state transition model through simulation together with evaluation of energy utilisation and productivity (Hibino et al., 2014). A robust framework for developing sustainable production in manufacturing companies is presented with lower damaging effects upon the environment (Abdullahi and Abdullah, 2015). Besides, the competitiveness and sustainable management of corporate entities are characterised by a set of benchmark indicators in modern socio-economic systems (Krivorotov et al., 2016). Such measurement indices for sustainable product development supported a reference methodology to accomplish sustainability in the manufacturing sector. Life cycle analysis of different products and services is assessed by Koltun (2010) to mitigate greenhouse gas emissions for promoting sustainability and eco-efficiency in aluminium industry. However, it did not deploy the intelligent design architecture of genetic optimisation to potentially eliminate the greenhouse effect. A comprehensive list of evaluation metrics for assessing the sustainability performance at product and process level has also been presented (Lu et al., 2011). Sustainability measures for rapid prototyping processes have been developed by (Ullah et al., 2013), conjoined with the estimation of energy consumption, carbon dioxide emissions and footprint. Iwaro and Mwasha (2013) analysed the performance of sustainable envelope design in building industries, together with the energy optimisation accomplished through green building concept. Also, Sirija (2013) specified the concept of green architectural practices and usage of reclaimed materials for sustainable development and resources efficiency.

Furthermore, the implementation of business operations by incorporating economically sustainable practices have been considered by Hami et al. (2015) for performance enhancement related to productivity and innovation capabilities. In contrast, sustainability-driven issues from environmental perspective are examined with regards to conducive business ecosystems at the organisational level (Rajala et al., 2016). An overview of measuring sustainability associated with the product design is provided for prototypical manufacturing systems (Singh and Sultan, 2017). In context to the green sustainable development, work by Patil and Patil (2017) examined prudent determination of eco-friendly raw materials for incorporating sustainable practices in building industries. Recently, a review study discussing the need for an effective sustainable system has been presented with detailed implementation techniques (Kishawy et al., 2018). In addition, it provided various performance indicators including product cost and wastage indicators for modelling and development of sustainable manufacturing process. Danso (2018) applied the sustainable technology in the field of construction materials and reviewed several key indicators for measuring its sustainability based on environmental, social, and economic disciplines. The body of work by Gültekin et al. (2018) reviewed the sustainable building design in the context of construction sector for dealing with environmental pollution and economic sustainability through public awareness. Beyond this, sustainability issues have been explored to reduce carbon dioxide emissions into the atmosphere from building materials owing to lower energy usage (Chel and Kaushik, 2018). This energy conservation is accomplished through feasible renewable energy technologies required for resource efficiency and minimal environmental deterioration. Papetti et al. (2018) explored the internet-of-things (IoT) framework to assess overall sustainability and productivity in manufacturing systems from social perspective. A multi-objective optimisation model based on fuzzy logic has been presented for sustainable manufacturing systems (Nujoom et al., 2018). In this model, different objectives considered for optimisation included energy conservation, economic profit and reduction of carbon dioxide emissions. A brief overview of the sustainable agriculture practices is presented in Arora (2019) through the intense climate change conditions and exacerbated discharge of the greenhouse gases into the environment. The impact of marine organic chemical fertilisers on the environmental sustainability in coastal areas while restoring the quality of soil for efficient land management is investigated by Emadodin et al. (2020). The high-risk effects of thermal power plants based on the coal utilisation and hazardous pollutants degrading the ecosystem are assessed through the simulative evaluation in Kalidasan et al. (2021). Moreover, the emissions of various speculative gases including CO_2, SOx, NOx, etc. are measured via the gasification procedure. A multi-objective sustainable machining optimisation model is implemented coupled with the application of the non-dominated sorting mechanism to retrieve optimal design parameters in the feasible manufacturing process (Salem et al., 2021). In a similar way, multi-criterion decision-making technique is employed for the ecological integrity assessment and sensitivity analysis of manufacturing industry encompassing the three disparate dimensions of sustainability (Saad et al., 2019). Besides, the minimum quantity lubrication and cryogenic machining procedures are jointly applied to accomplish the enhanced productivity, material durability and sustainable machining performance (Jawahir et al., 2020).

1.3 Scientific contribution

In this paper, we develop empirical assessment of alternative sustainability paradigm while considering the environment protection considerations. The goal of sustainability in product manufacturing is to maintain the balance between energy conservation and cost benefits, and at the same time demonstrating continuous environmental performance improvements. To achieve these objectives, an evaluation framework is implemented that deals with the monitored utilisation of sustainable products in the field of material manufacturing technology. As opposed to the previous related works, the composition of various global environment metrics including greenhouse gas emissions, ocean acidification, water management and wastewater treatment techniques are illustrated for low and high product recyclability case models employed in the complex manufacturing scenarios. Through simulation experiments, reduction in greenhouse gas emissions and overall energy consumption are assessed for various types of materials influencing the quality of environment. This analysis framework provides a more robust structure to expedite the material selection which is more sustainable and eco-friendly for product development in manufacturing systems. Such thorough assessment and sustainable analyses of the manufacturing system design has not been implemented in the past research. In addition, a non-constrained optimisation problem is formulated for alleviating the greenhouse gas emissions. For this, the evolutionary genetic algorithm scheme is iteratively executed for assessing the optimal solution by contemplating the impact of various selection, crossover and mutation techniques in the application of the genetic model. This system model is examined for the effective meta-heuristic design and searching through the feasible solution space. To the best of our knowledge, no prior work has applied the genetic optimisation strategy coupled with the recycling scheme in the context of sustainable manufacturing development. Furthermore, simulation results are presented to show the performance enhancement of the proposed system model over the existing models in terms of various ecological metrics including greenhouse gas emissions, energy efficiency and average carbon footprint. Environmental performance improvements quantified by these diverse and multiple metrics identified from the literature are intended to make the production process as sustainable. The developed simulative evaluation framework can be employed by engineers, research organisations and policy-makers in the early stages of production and manufacturing with the primary focus on environmental sustainability concerns.

2 Material and methods

In this work, we have not developed a generalised framework that is applicable to all kinds of manufacturing systems which can range from continuous manufacturing including process production used in mining and food production industries, discrete manufacturing using the assembly line, intermittent batch production, to flexible manufacturing systems. Rather, we specifically contemplate and analyse the self-evolving sustainable manufacturing systems that are mainly aimed to develop manufacturing processes, materials, recycling methods, waste management methods, software tools, and efficient pollution control strategies that will finally yield the manufactured products used in the day-to-day life with the mitigated energy consumption and reduced environmental footprint. The concept of sustainability aims at alleviating the pernicious environmental effects, while simultaneously raising the quality of living standards. The major driving factors of the need for sustainability in the modern-day system design include energy constraints, limited resources, global warming, changing customer requirements, government initiatives, carbon credits, rapid demand changes, etc. The crucial goal of any production system is to develop and manufacture more sustainable products that are exhaustively recyclable and exhibit lower damaging impacts on the natural environment. In an attempt to integrate sustainability issues in manufacturing and production domains, several ecological metrics are evaluated affecting water management, energy utilisation, climate change, air quality and greenhouse gas impact. These metrics are intended to achieve environmental benefits by sustainable production on account of lower waste generation and disposal, and reduced carbon dioxide emissions.

Overall energy consumption based on the type of material and the amount of its recycled content is essential to determine the energy efficiency associated with each product type and subsequent potential of reusability on energy savings. In the present work, different products employed in manufacturing are compared and assessed based on their waste production, emissions and net energy consumption for two case studies relating to recyclability. For this, a series of simulation experiments are conducted using MATLAB software tool. These simulations are performed for implementing sustainable practices incorporated in green manufacturing operations considering various environmental aspects and energy consumption based on material recyclability. In this work, we formulate a simulation model to develop a framework for sustainability assessment in manufacturing systems. This model represents the instantiation/abstraction containing only relevant details of the presented model using simplifying assumptions. This simulation model is the time-dependent computer modelling of how the system will behave as time progresses. In general, simulation can be referred to as a technique of employing computers to imitate the behaviour of systems over time using mathematical models. The wastewater related indices such as COD, BOD and TSS assume that the experiments are performed with a sealed sample of water at a controlled temperature of around 20 degrees centigrade over a predetermined time interval of five days. Besides, the application of the International Organisation for Standardisation (ISO) 14060 is contemplated that details principles for identifying greenhouse gas emissions through the combustion of fuels, and net energy consumption for several materials used in the manufacturing industry.

Apart from this, the proposed work differs from the earlier works in literature stated in the previous section in that the presented analysis can facilitate the selection of materials which are more sustainable and eco-efficient for product design in manufacturing industries. Further, the environmental metrics associated with each material aim at identification of the products (services) with better potential as a structural material on the basis of the same scale. Thus, the overall manufacturing system can be transpositioned to a higher sustainable level with significant increase of recycled content. We have employed the global scales of environmental concern incorporating the pollution of the atmosphere and the oceans, climate change and global warming due to greenhouse gas emissions, accumulation of solid wastes, etc. In the proposed work, these issues can be resolved for sustainable manufacturing through the recycling and genetic optimisation procedures.

3 Results and discussion

In this study, an estimate of environmental impacts of the product is provided based on selected case studies of 20% (low recyclability) and 80% (high recyclability) of the recycled content. The two recyclability proportions of 0.2 and 0.8 are randomly selected in accordance with the low and high recycled content of the product. This is implemented to demonstrate the effects of both the nominal and substantial extremes of recycling measure on the proposed sustainable manufacturing design model. The composition of greenhouse gas emissions, ocean acidification and solid waste generated by utilising different types of products in manufacturing organisations is illustrated in Figure 2 and Figure 4 for both recyclability cases. In case of 20% recycled content, the greenhouse gas emissions are 85.67% and 88.12% higher than ocean acidification and solid wastes generated, respectively. For 80% recyclability, these emissions are 78.36% and 92.56% more compared with ocean and solid wastes, respectively. Thus, greenhouse gas emissions have a considerably major impact on the global climate in contrast to other waste materials. Besides, the greenhouse gas emissions are cumulatively reduced by around 45.96% through the recycling process by increasing the recycled content from 20% to 80%. Similarly, the ocean acidification and solid waste composition are alleviated by 18.42% and 66.16%, respectively for the examined increment in recyclability proportion. In the same way, Figure 3 and Figure 5 plot several indicators for each product related to water management and wastewater treatment techniques such as SO_2, COD, BOD, TSS, and air quality indicators reflecting the HAP. It can be observed that the COD has the maximal hazardous contribution to the environment with an average value of 122.67 pounds and 108.617 pounds for 20% and 80% recyclability cases, respectively. Through the execution of recycling mechanism in the proposed system by up to 80%, the SO_2, COD, BOD, TSS, and HAP measures are accordingly improved by 17.42%, 11.45%, 17.07%, 43.32%, and 27.56%. It can be observed that the superlative manufacturing system performance by employing the recycling technique is encountered in the context of greenhouse gas emissions, solid waste, and aggregate waterborne particles that remain in suspension in water.

Figure 2 Composition of greenhouse gas emissions, ocean acidification and solid waste generated for different types of products in manufacturing based on 20% recyclability (see online version for colours)

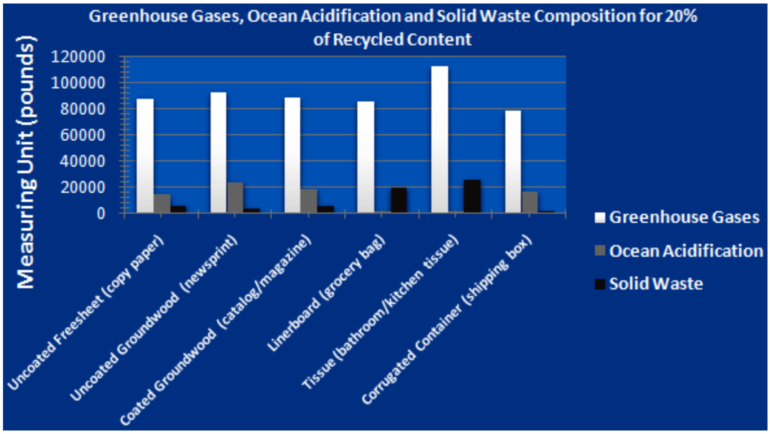
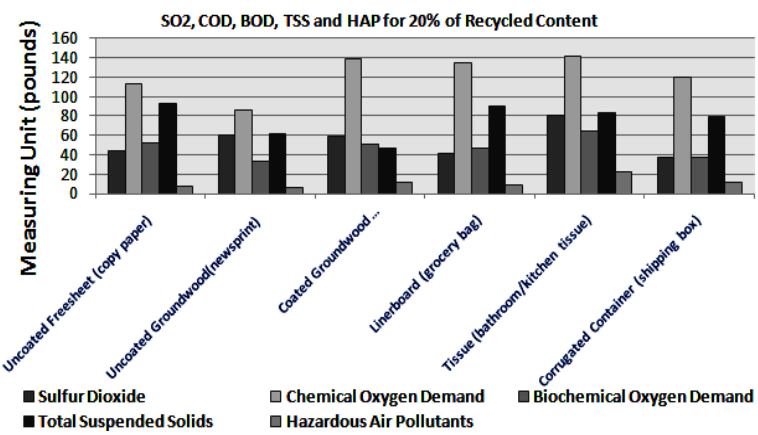


Figure 3 Composition of SO_2, COD, BOD, TSS and HAP for different types of products in manufacturing based on 20% recyclability (see online version for colours)



Recycling of various types of materials employed in manufacturing sector can typically save more energy consumption in the production process, while addressing the major concerns of resource depletion. The potential of recycling and reprocessing of the waste materials for reducing the greenhouse gas emissions, and benefiting the environment as well as the community is demonstrated in Figure 6. It can be observed from the graph that recycling and composting of metal scrap achieves maximum reduction in greenhouse gas emissions, while minimal reductions are accomplished by recycling of broken glass. Energy-intensive manufacturing industries consume enormous amount of energy for production processes. This conceptualisation is comprehended to facilitate the critical management of valuable energy resources, sustainable policy development, lowering of environmental impact, scaling down utility bills, etc. Figure 7 illustrates the overall energy consumption based on the percentage of recycled content for different types of materials. This recycled content is computed as a significant percentage of the weight of the reused core manufacturing product. To compute the net energy usage, the formula specification that is deployed considers various complex factors including power utilised by manufacturing organisations for the production mechanism, time over which energy was consumed, system efficiency, environmental conditions, rules of production process such as production rate, availability and quality of information and data, system boundaries such as energy used by the essential construction equipments including machinery, materials, technology, manufacturing plants, personnel equipment, etc. It can be noticed that the corrugated container exhibits the most energy-efficient material for product development in the manufacturing sector. The average carbon emissions generated through the production of manufactured goods and other services for people in various countries is plotted in Figure 8. These emissions are usually expressed as carbon dioxide equivalent for a definite population of a country. In terms of country average on global context, the USA has the highest carbon footprint, whereas the Philippines have the lowest with under 1.2 metric tons per capita.

Figure 4 Composition of greenhouse gas emissions, ocean acidification and solid waste generated for different types of products in manufacturing based on 80% recyclability (see online version for colours)

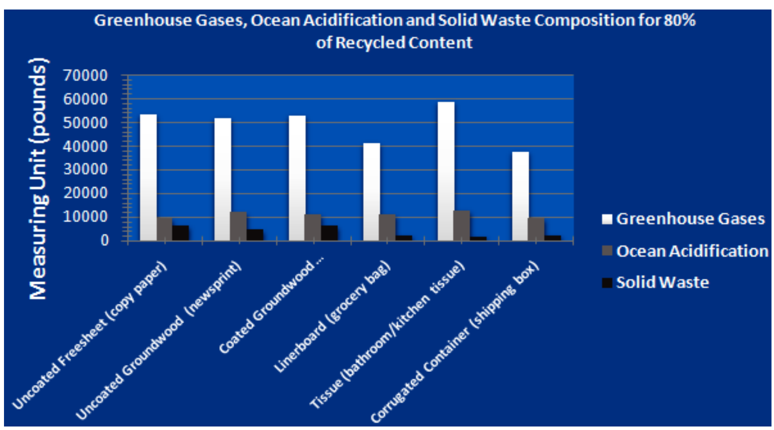


Figure 5 Composition of SO_2, COD, BOD, TSS and HAP for different types of products in manufacturing based on 80% recyclability (see online version for colours)

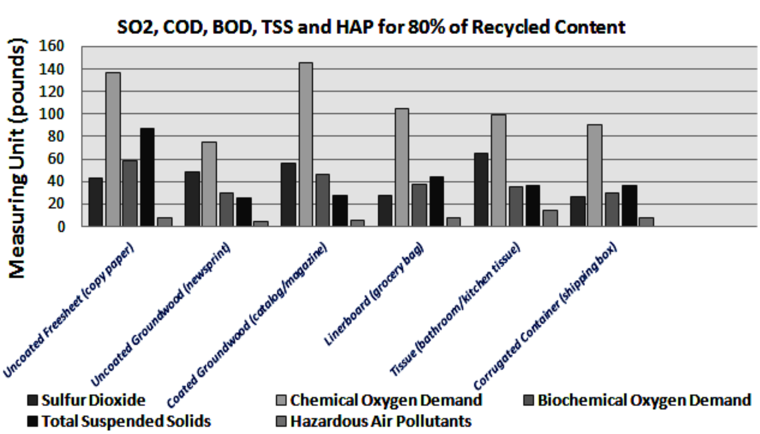


Figure 6 Greenhouse gas reduction imposed by recycling/composting for different types of products in manufacturing

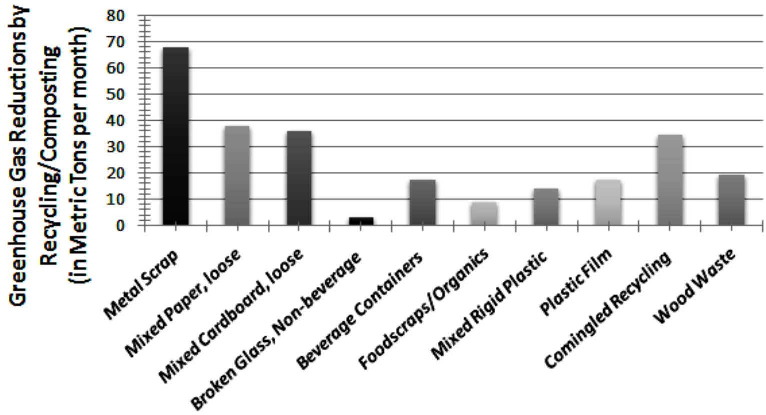


Figure 7 Net energy consumption varying as a function of percentage of recycled content of different types of material usage (see online version for colours)

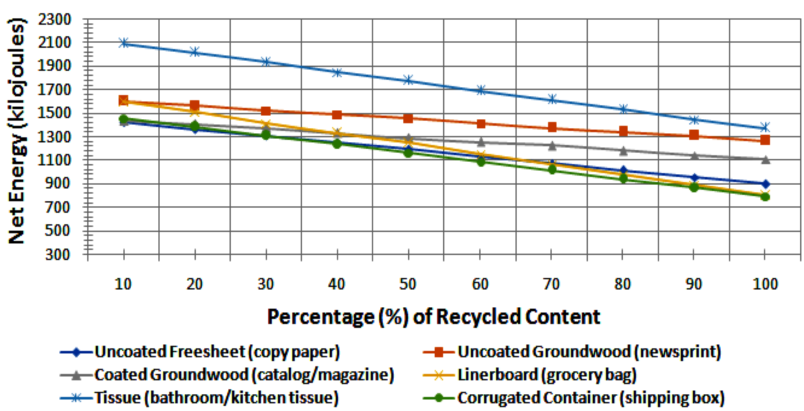


Figure 8 Average carbon footprint for people in different countries (see online version for colours)

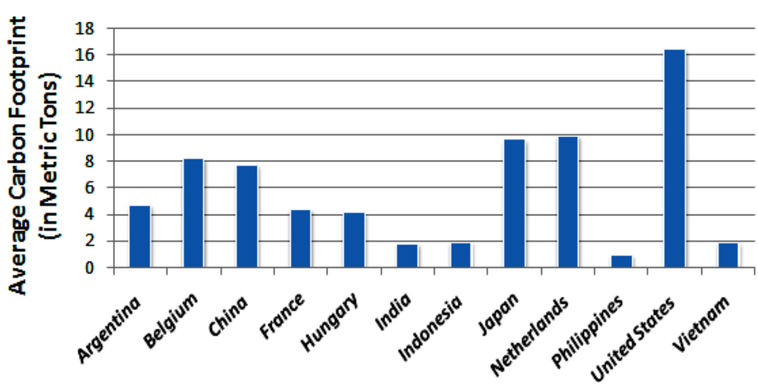


Table 1 Sensitivity analysis of the proposed model for different manufacturing products

	Greenhouse gas emissions	*Ocean acidification*	*Solid waste composition*	SO_2	*COD*	*BOD*	*TSS*	*HAP*
Uncoated freesheet (copy paper)	583.33	66.67	25	0.0167	0.383	0.1	0.067	0.017
Uncoated groundwood (newsprint)	666.67	183.33	25.66	0.183	0.183	0.083	0.583	0.05
Coated groundwood (catalogue/ magazine)	566.67	116.67	8.33	0.05	0.083	0.0916	0.316	0.1
Linerboard (grocery bag)	725	158.33	300	0.216	0.55	0.15	0.8	0.016
Tissue (bathroom/ kitchen tissue)	883.33	200	425	0.267	0.7	0.43	0.75	0.116
Corrugated container (shipping box)	683.33	100	4.7	0.217	0.467	0.117	0.7	0.067

Table 2 Uncertainty analysis of the proposed model for different manufacturing products

	Greenhouse gas emissions	*Ocean acidification*	*Solid waste composition*	SO_2	*COD*	*BOD*	*TSS*	*HAP*
Uncoated freesheet (copy paper)	0.529	0.51643	0.464	0.12618	0.47478	0.3857	0.279	0.35237
Uncoated groundwood (newsprint)	0.5225	0.50864	0.4422	0.4644	0.3795	0.3576	0.449	0.5283
Coated groundwood (catalogue/ magazine)	0.53	0.5299	0.401	0.16346	0.1947	0.288	0.527	0.45387
Linerboard (grocery bag)	0.4974	0	0.1368	0.5307	0.4863	0.4389	0.4923	0.482
Tissue (bathroom/ kitchen tissue)	0.511	0	0.0839	0.4644	0.5182	0.5284	0.4819	0.52567
Corrugated container (shipping box)	0.4846	0.5307	0.4422	0.5283	0.4952	0.4882	0.4881	0.51125

Next, we perform the sensitivity analysis, which is computed as the ratio of the percentage change in output parameters to the percentage change in input parameters. Here, the input parameter corresponds to the proportion of the recycled content of the manufacturing products. Moreover, the output parameters are the composition of greenhouse gas emissions, ocean acidification, solid waste generated, SO_2, COD, BOD, TSS and HAP measures for different types of products in the manufacturing system. Table 1 demonstrates the sensitivity analysis for each of the contemplated products in the proposed manufacturing model. It can be computationally assessed that the tissue (bathroom/kitchen tissue) product exhibits the maximal sensitivity, while the uncoated freesheet and coated groundwood manufacturing products yield the minimal sensitivity on an average for each considered output parameter measuring the ecological impact. Likewise, the uncertainty analysis of the developed manufacturing system is illustrated in Table 2. The uncoated groundwood (newsprint) has the greatest mean uncertainty measure of approximately 0.456, and hence the highest cost associated with the sustainable implementation perspective in the manufacturing design model.

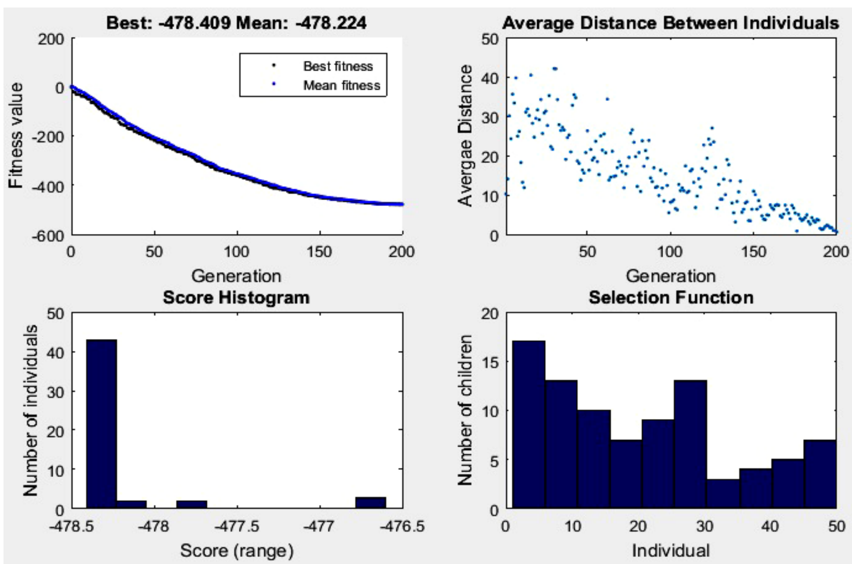
3.1 Genetic algorithm implementation of the proposed sustainable manufacturing model

In this section, the optimisation of the presented sustainable manufacturing system is implemented through the application of the evolutionary genetic algorithm approach. This is accomplished by executing the iterative simulations of the optimisation model using the genetic algorithm in global optimisation toolbox of MATLAB software. The unconstrained optimisation problem for reduced emissions of greenhouse gases generated from the manufacturing activities is formulated as:

$$\textit{minimise} \quad \eta x$$

Here, η is the scaling factor determined by the specific greenhouse gas, and x is the singleton optimisation variable of the fuel gas consumption. For instance, the constant factor η is 0.04032 for NOx gas, 0.33528 for SO_2 gas, etc. (Li et al., 2018). Table 3 illustrates the simulation parameter settings at which the genetic methodology is executed to implement the presented manufacturing system problem. Some of these parameters are set to their optimal values, while others are initialised to the default setting values in genetic algorithmic setup in the MATLAB software. Moreover, three disparate combinations of selection, mutation and crossover function types are utilised to evaluate their varying impact on the performance of the developed optimisation model. The other optimisation methods such as particle swarm optimisation, ant colony optimisation techniques can be applied to the presented sustainable manufacturing system as a subject of future research work. In this work, genetic algorithm is applied since it is an adaptive heuristic search algorithm to solve complicated problems with higher number of variables to find the most optimal solution. Besides, no prior work in the field of sustainable manufacturing design has applied this multi-objective optimisation technique of artificial intelligence and computing framework to obtain the best possible outcomes for a complex problem that improve over time horizon. Figure 9 demonstrates the plots displaying the optimal fitness value, the average distance measure between individual neighbouring solutions, the score histogram specifying the score of individual solutions, and the roulette selection function, for the Gaussian mutation and Two-point crossover operations. Besides, Figures 10 and 11 depict the corresponding plots for the tournament, adaptive feasible, heuristic functions, and uniform, constraint dependent, arithmetic genetic operations, respectively. The number of generations' parameter and the size of the individuals are varied to plot the fitness value, selection function and the average distance measure between individuals. In this iterative search technique, a population of candidate solutions with lower rank are selected with higher probability in the subsequent iteration. Negative values of the objective function are retrieved owing to the fact that we minimise the emissions of greenhouse gases generated in the environment. Although the fitness functions value is implicitly maximised in the genetic algorithm module. Through the experimental results, it was found that the minimal amount of greenhouse gases of 58.57 metric tons are associated with the tournament selection function with size of 2, adaptive feasible mutation and heuristic crossover operations.

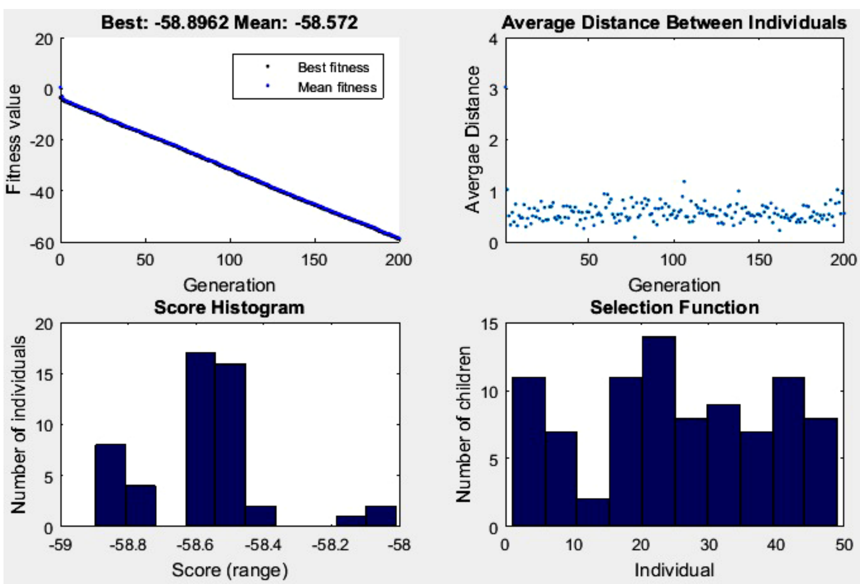
Figure 9 Plot illustrating the best fitness value, the average distance between individuals, the score histogram, and the roulette selection function, for the Gaussian mutation and two-point crossover operations (see online version for colours)



3.2 *Cost analysis of the proposed model*

Furthermore, cost analysis is performed to serve as a prediction tool to compute the proposed model's overall computational costs. Suppose variable r represents the percentage of the recycled content, and q denotes the set of employed manufacturing products for the developed sustainable design modelling. Then, the computational complexity associated with the evaluation of each environment quality indicator is $O\left(\left(\frac{r}{100}\right) * \sum_{i=1}^{|q|} q[i]\right)$, where $|q|$ represents the cardinality of the set q, and $q[i]$ is the i^{th} element of the considered set of manufacturing products. This cost increases in direct proportion to the ratio of recycled materials and the total number of considered manufacturing products deployed in the fabrication industrial processing. The net energy consumption for the product manufacturing takes the statistical complexity of $O\left(\omega*\left(\frac{t}{1{,}000}\right)*|q|*\left(\frac{r}{100}\right)\right)$, where ω is the power measured in watts, and t is the effective period of time over which the energy utilised in product manufacturing was consumed. Additionally, the cost corresponding to the execution of the sensitivity analysis in the proposed manufacturing design structure is $O\left(\sum_{i=1}^{|q|}\frac{q[i]}{r}\right)$, while that connected with the uncertainty analysis is $O\left(P(x)*\log\left(\frac{1}{P(x)}\right)\right)$. Here, x represents the ratio of the manufacturing products constructed with a given recyclability proportion to the synthesised products obtained with the maximal permitted recycled fraction, and $P(x)$ is the probability of x. Finally, the genetic algorithm implementation of the proposed manufacturing design model requires $O\left[k*(2*s*m+s)*|q|*\left(\frac{r}{100}\right)\right]$ iterations, where k is the number of generations, s is the population size, and m is the size the individuals.

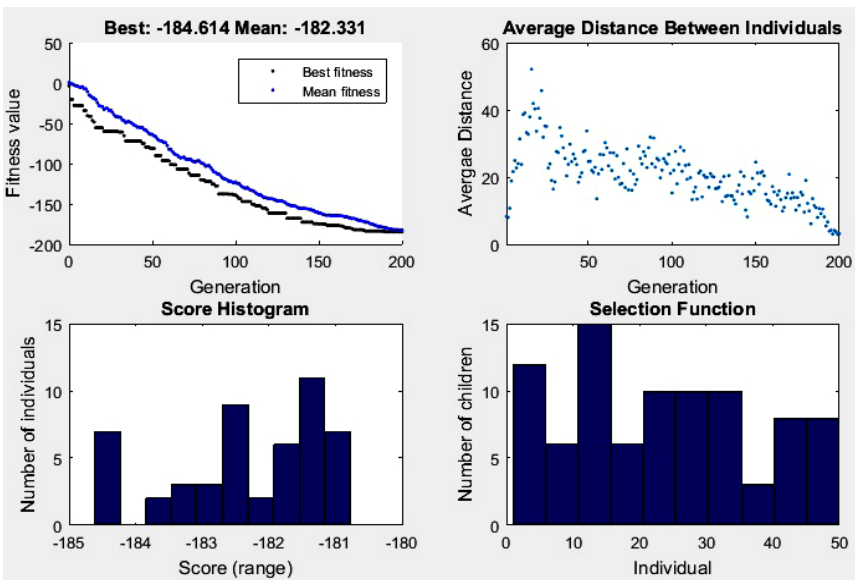
Figure 10 Plot illustrating the best fitness value, the average distance between individuals, the score histogram, and the tournament selection function, for the adaptive feasible mutation and heuristic crossover operations (see online version for colours)



3.3 Performance comparison with previous works

In this subsection, the performance of the presented work is compared with the five related existing works in literature, as shown in Table 4. Among these works, Loyarte-López et al. (2020) applied environmental awareness and climate change metrics for the research and development activities implemented in technology organisations. Energy conservation and controlled emissions are enforced in mining and beneficiation operations executed in the iron and steel industry for analysis of the plant-specific process data (Wei et al., 2020). The average carbon footprint and energy consumption of machinery usage, fertilisers, and fossil fuels contributing to total greenhouse gas emissions is estimated for pastoral and barn dairy farming systems in Ilyas et al. (2019). Besides, Wakeland et al. (2012) considered the transportation-related and storage-linked issues associated with food production and supply systems in the context of energy cost, carbon assessments and product's aggregate emissions. Cioca et al. (2015) investigated the impact of four domains on carbon dioxide emissions from the organisational perspective, viz., energy, transport, waste and industrial domains. Their approach contemplated the effects of pollution and natural climate change on the sustainable development of business models in Romania.

Figure 11 Plot illustrating the best fitness value, the average distance between individuals, the score histogram, and the uniform selection function, for the constraint dependent mutation and arithmetic crossover operations (see online version for colours)



Despite these previous works, the approach in the presented work considers the recycling process of waste materials destined for manufacturing new products with minimal greenhouse gas emissions and reduced energy consumption for maintaining the sustainable environment. Different types of materials are exploited to evaluate these ecological-enduring parameters for product development in manufacturing industries. The metrics employed for the purpose of comparison include the net greenhouse gas emissions, mean energy consumption and average carbon footprint. It can be estimated that the proposed model exhibits up to 85.4% reduction in greenhouse gas emissions and 72.86% lower carbon footprint in contrast to the previous models. In addition, our work achieves energy efficiency by a maximal factor of 247.13. This performance enhancement is attributed to the fact that the developed design framework utilised higher recycled content together with alleviated waste generation during material development in the manufacturing process. The indicated reduction in the carbon footprint production in the proposed manufacturing design leads to the lower global warming effects and climate change conditions. This ambience setting further causes diminishing number of human respiratory infections and even less aggressive behaviour with negligible violence promoting the overall nation's social and ecological growth.

Table 3 Simulation setup parameters for genetic algorithm

Parameter name	*Value*
Simulation software	MATLAB
Fitness scaling function	Rank
Creation function	Constraint dependent
Selection function	Roulette, tournament, uniform
Mutation function	Gaussian, adaptive feasible, constraint dependent
Crossover function	Two-point, heuristic, arithmetic
Crossover fraction	0.8
Migration direction	Forward
Migration fraction	0.2
Migration interval	20
Nonlinear constraint algorithm	Augmented Lagrangian
Initial penalty	10
Penalty factor	100
Time limit	Infinity
Fitness limit	Negative infinity
Stall generations	50
Stall time limit	Infinity
Stall test	Average change
Function tolerance	10^{-6}
Constraint tolerance	10^{-3}
Maximum number of iterations	200

Table 4 Performance comparison of the proposed model with previous works

	Greenhouse gas emissions (pounds)	*Mean energy consumption (kilojoules)*	*Average carbon footprint (metric tons)*
Proposed model	51,540	1,438	1.985
Model in Loyarte-López et al. (2020)	168,978	355,372	7.314
Model in Wei et al. (2020)	177,500	161,760	3.165
Model in Ilyas et al. (2019)	230,150	17,846	3.724
Model in Wakeland et al. (2012)	340,150	25,335	4.94
Model in Cioca et al. (2015)	352,918	48,675	4.7

4 Conclusions

Sustainable development plays a substantial role in manufacturing industries to mitigate the negative impacts of product manufacturing on the environment. In addition, sustainability is imperative for achieving economic efficiency through system growth, productivity, accessibility, combined with the controlled energy consumption. The presented work provides an evaluation framework that deals with the pressing challenge of sustainability in emerging areas of material manufacturing. The composition of various environment metrics including greenhouse gas emissions, ocean acidification, water management and wastewater treatment techniques are demonstrated for low and high material recyclability employed in the manufacturing system. Through simulation experiments, reduction in greenhouse gas emissions and net energy utilisation are evaluated for various types of materials employed in manufacturing sector. This analysis framework provides a robust structure to facilitate the selection of materials which are more sustainable and eco-efficient for product design in manufacturing systems. We also demonstrate the average annual carbon footprint per individual for different countries, indicated by the metric tons of net emissions. Further, it is anticipated that this research study can be conferred as a guideline for researchers and decision-makers to enhance sustainable product design in the manufacturing sector based on the concept of recyclability. Analyses of sensitivity and uncertainty measures are implemented for each of the deployed products in the proposed sustainable manufacturing model. It can be computationally assessed that the tissue product exhibits the highest sensitivity measure, while the uncoated freesheet and coated groundwood manufacturing products yield the least average sensitivity for all the ecological output parameters. The uncoated groundwood has the maximum mean uncertainty measure of around 0.45, and thus the highest cost associated with the sustainable development perspective in the manufacturing design model.

The implementation of the evolutionary genetic algorithm technique is recurrently executed for acquiring the optimal solution of minimal gas emissions by considering the influence of different selection, crossover and mutation methods in the application of genetic methodology. This optimisation model is rigorously investigated for the proficient meta-heuristic design and searching through the enormous feasible solution space. Finally, we compare the performance of our design model with the previous models in terms of several environment quality metrics. It has been observed that the proposed system demonstrates more than 85% reduced emissions and 72% lessened carbon footprint owing to appropriate selection of ecological-friendly materials for product manufacturing. Moreover, the developed model implements energy-efficient operation due to increased recycling and composting deployment with minimal 91.94% improved energy conservation.

In future, the proposed model is recommended to be consequently verified and validated for other types of manufacturing products to ensure the generality and effectiveness of the modelling framework in achieving sustainability from economic growth and environmental perspectives. Since the proposed work focuses on environmental and energy metrics to exhibit sustainability in product development, other social and economic performance indices can be employed in future research that seeks to assess the sustainable design in manufacturing.

References

Abdullahi, T. and Abdullah, S.S. (2015) 'Sustainability considerations in manufacturing and operation management', *International Journal of Scientific Engineering and Applied Science (IJSEAS)*, Vol. 1, No. 4, pp.490–497.

Arora, N.K. (2019) 'Impact of climate change on agriculture production and its sustainable solutions', *Environmental Sustainability*, Vol. 2, pp.95–96, DOI: 10.1007/s42398-019-00078-w.

Chel, A. and Kaushik, G. (2018) 'Renewable energy technologies for sustainable development of energy efficient building', *Alexandria Engineering Journal*, Vol. 57, No. 2, pp.655–669.

Cioca, L-I., Ivascu, L., Rada, E.C., Torretta, V. and Ionescu, G. (2015) 'Sustainable development and technological impact on CO2 reducing conditions in Romania', *Sustainability*, Vol. 7, No. 2, pp.1637–1650, DOI: 10.3390/su7021637.

Danso, H. (2018) 'Identification of key indicators for sustainable construction materials', *Advances in Materials Science and Engineering, Special Issue: Sustainable Building Materials and Technologies*, Article ID: 6916258, Vol. 2018, 7p, DOI: 10.1155/2018/6916258.

Emadodin, I., Reinsch, T., Rotter, A. et al. (2020) 'A perspective on the potential of using marine organic fertilizers for the sustainable management of coastal ecosystem services', *Environmental Sustainability*, Vol. 3, pp.105–115, DOI: 10.1007/s42398-020-00097-y.

Ganda, F. and Ngwakwe, C.C. (2014) 'Role of energy efficiency on sustainable development', *Environmental Economics*, Vol. 5, No. 1, pp.86–99.

Gültekin, A.B., Yıldırım, H.Y. and Tanrıvermiş, H. (2018) 'A holistic conceptual scheme for sustainable building design in the context of environmental, economic and social dimensions', in book: *Sustainable Buildings – Interaction Between a Holistic Conceptual Act and Materials Properties*, pp.19–47, InTech, Sweden, DOI: 10.5772/intechopen.74031.

Hami, N., Muhamad, M.R. and Ebrahim, Z. (2015) 'The impact of sustainable manufacturing practices and innovation performance on economic sustainability', *12th Global Conference on Sustainable Manufacturing, Procedia CIRP*, Vol. 26, pp.190–195.

Hariyani, D., Mishra, S., Hariyani, P. and Sharma, M.K. (2023) 'Drivers and motives for sustainable manufacturing system', *Innovation and Green Development*, Vol. 2, No. 1, p.100031, DOI: 10.1016/j.igd.2022.100031.

Hibino, H., Sakuma, T. and Yamaguchi, M. (2014) 'Simulation for sustainable manufacturing system considering productivity and energy consumption', *IFIP International Conference on Advances in Production Management Systems (APMS)*, pp.310–318, DOI: 10.1007/978-3-662-44736-9_38.

Ilyas, H.M.A., Safa, M., Bailey, A., Rauf, S. and Pangborn, M. (2019) 'The carbon footprint of energy consumption in pastoral and barn dairy farming systems: a case study from Canterbury, New Zealand', *Sustainability*, Vol. 11, No. 17, p.4809, DOI: 10.3390/su11174809.

Iwaro, J. and Mwasha, A. (2013) 'The impact of sustainable building envelope design on building sustainability using integrated performance model', *International Journal of Sustainable Built Environment*, Vol. 2, No. 2, pp.153–171.

Jawahir, I.S., Schoop, J., Kaynak, Y., Balaji, A.K., Ghosh, R. and Lu, T. (2020) 'Progress toward modeling and optimization of sustainable machining processes', *ASME Journal of Manufacturing Science and Engineering*, Vol. 142, No. 11, p.110811, 31p, DOI: 10.1115/1.4047926.

Kalidasan, B., Deepika, K., Shankar, R. et al. (2021) 'Numerical simulation of emission gas in coal thermal power plant for sustainable development', *Environmental Sustainability*, DOI: 10.1007/s42398-021-00180-y.

Kannan, D., Gholipour, P. and Bai, C. (2023) 'Smart manufacturing as a strategic tool to mitigate sustainable manufacturing challenges: a case approach', *Annals of Operations Research*, 37p, DOI: 10.1007/s10479-023-05472-6.

Kishawy, H.A., Hegab, H. and Saad, E. (2018) 'Design for sustainable manufacturing: approach, implementation and assessment', *Sustainability*, *Open Access Journal*, Vol. 10, No. 10, pp.1–15, MDPI, DOI: 10.3390/su10103604.

Koltun, P. (2010) 'Materials and sustainable development', *Progress in Natural Science: Materials International*, Vol. 20, No. 1, pp.16–29, DOI: 10.1016/S1002-0071(12)60002-1.

Krivorotov, V.V., Kalina, A.V., Belyaeva, Z.S. and Erypalov, S.Y. (2016) 'Optimisation model for industrial complex competitiveness: a path to sustainable innovation process', *World Review of Entrepreneurship, Management and Sustainable Developmen*t, Vol. 12, Nos. 2/3, pp.254–269.

Li, M., Klimont, Z., Zhang, Q., Martin, R.V., Zheng, B., Heyes, C., Cofala, J., Zhang, Y. and Kebin He, K. (2018) 'Comparison and evaluation of anthropogenic emissions of SO2 and NOx over China', *Atmospheric Chemistry and Physics*, Vol. 18, pp.3433–3456, DOI: 10.5194/acp-18-3433-2018.

Lin, C., Choy, K.L., Ho, G.T. and Ng, T.W. (2014) 'A genetic algorithm-based optimization model for supporting green transportation operations', *Expert Systems with Applications*, Vol. 41, No. 7, pp.3284–3296, DOI: 10.1016/j.eswa.2013.11.032.

Loyarte-López, E., Barral, M. and Morla, J.C. (2020) 'Methodology for carbon footprint calculation towards sustainable innovation in intangible assets', *Sustainability*, Vol. 12, No. 4, p.1629, DOI: 10.3390/su12041629.

Lu, T., Gupta, A., Jayal, A.D., Badurdeen, F., Feng, S.C., Dillon, O.W. and Jawahir, I.S. (2011) 'A framework of product and process metrics for sustainable manufacturing', in *Advances in Sustainable Manufacturing*, Springer, Berlin, Heidelberg, DOI: 10.1007/978-3-642-20183-7_48.

Mensah, J. (2019) 'Sustainable development: meaning, history, principles, pillars and implications for human action: literature review', *Cogent Social Sciences*, Vol. 5, No. 1, DOI: 10.1080/23311886.2019.1653531.

Nujoom, R., Mohammed, A. and Wang, Q. (2018) 'A sustainable manufacturing system design: a fuzzy multi-objective optimization model', *Environmental Science and Pollution Research*, Vol. 25, No. 25, pp.24535–24547, DOI: 10.1007/s11356-017-9787-6.

Papetti, A., Gregori, F., Pandolfi, M., Peruzzini, M. and Germani, M. (2018) 'IoT to enable social sustainability in manufacturing systems', *Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0*, Vol. 7, pp.53–62, DOI: 10.3233/978-1-61499-898-3-53.

Patil, K.M. and Patil, M.S. (2017) 'Sustainable construction materials & technology in context with sustainable development', *International Journal of Engineering Research and Technology*, Vol. 10, No. 1, pp.112–117.

Paul, I.D., Bhole, J.P. and Chaudhari, J.R. (2014) 'A review on green manufacturing: it's important, methodology and its application', *Procedia Materials Science*, Vol. 6, pp.1644–1649.

Rajala, R., Westerlund, M. and Lampikoski, T. (2016) 'Environmental sustainability in industrial manufacturing: re-examining the greening of Interface's business model', *Journal of Cleaner Production*, 1 March, Vol. 115, pp.52–61.

Saad, M.H., Nazzal, M.A. and Darras, B.M. (2019) 'A general framework for sustainability assessment of manufacturing processes', *Ecological Indicators*, Vol. 97, pp.211–224, DOI: 10.1016/j.ecolind.2018.09.062.

Sadeghi, J. and Haapala, K.R. (2019) 'Optimizing a sustainable logistics problem in a renewable energy network using a genetic algorithm', *OPSEARCH, Springer, Operational Research Society of India*, Vol. 56, No. 1, pp.73–90, DOI: 10.1007/s12597-019-00356-5.

Salem, A., Hegab, H. and Hossam A. and Kishawy, H.A. (2021) 'An integrated approach for sustainable machining processes: assessment, performance analysis and optimization', *Sustainable Production and Consumption*, Vol. 25, pp.450–470, DOI: 10.1016/j.spc.2020.11.021.

Sen, P.K., Bohidar, S.K., Shrivas, Y., Sharma, C. and Modi, V. (2015) 'Study on innovation, research and recent development in technology for green manufacturing', *International Journal of Mechanical Engineering and Robotics Research*, Vol. 4, No. 1, pp.185–194.

Singh, K. and Sultan, I. (2017) 'Framework for sustainability performance assessment for manufacturing processes – a review', *IOP Conference Series: Earth and Environmental Science*, Vol. 73, p.012029, DOI:10.1088/1755-1315/73/1/012029.

Sirija, M. (2013) 'Necessity of sustainability in architectural practices for achieving sustainable development', *Recent Research in Science and Technology*, Vol. 5, No. 5, pp.79–82.

Tambouratzis, T. (2016) 'A step-wise genetic-algorithm-based approach for improving the sustainability of any country and for determining the characteristics of the ideally sustainable country', *2016 IEEE Congress on Evolutionary Computation (CEC*), pp.2329–2336, DOI: 10.1109/CEC.2016.7744076.

Ullah, A.M.M.S., Hashimoto, H., Kubo, A. and Tamaki, J. (2013) 'Sustainability analysis of rapid prototyping: material/resource and process perspectives', *International Journal of Sustainable Manufacturing*, Vol. 3, No. 1, pp.20–36.

Ullah, S., Khan, F.U. and Ahmad, N. (2022) 'Promoting sustainability through green innovation adoption: a case of manufacturing industry', *Environmental Science and Pollution Research*, Vol. 29, No. 14, pp.21119–21139.

Vadoudi, K., Troussier, N. and Zhu, T.W. (2014) 'Toward sustainable manufacturing through PLM, GIS and LCA interaction', *International Conference on Engineering, Technology and Innovation (ICE)*, Bergamo, Italy, DOI: 10.1109/ICE.2014.6871545.

Wakeland, W., Cholette, S. and Venkat, K. (2012) 'Food transportation issues and reducing carbon footprint', in *Green Technologies in Food Production and Processing. Food Engineering Series*, pp.211–236, Springer, B oston, MA, DOI: 10.1007/978-1-4614-1587-9_9.

Wei, W., Samuelsson, P.B., Tilliander, A., Gyllenram, R. and Jönsson, P.G. (2020) 'Energy consumption and greenhouse gas emissions during ferromolybdenum production', *Journal of Sustainable Metallurgy*, Vol. 6, pp.103–112, DOI: 10.1007/s40831-019-00260-8.

Yoon, E-J. and Lee, D-K. (2017) 'Basic study on spatial optimization model for sustainability using genetic algorithm', *Journal of the Korean Society of Environmental Restoration Technology*, Vol. 20, No. 6, pp.133–149, DOI: 10.13087/kosert.2017.20.6.133.

Websites

https://www.worldometers.info/co2-emissions/co2-emissions-per-capita.