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Development of green manufacturing implementation framework based on life-cycle assessment

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Abstract

Climate change stabilization at 1.5 to 2 °C requires a shift in paradigm of industries to transition to low carbon industries. The way forward to decarbonize industries is green manufacturing, as the environmental facet of manufacturing has often been compromised for the sake of economic gains. In order to implicate green manufacturing, it is incumbent upon manufacturing facilities to introduce such measures which ensure that carbon footprint and environmentally detrimental emissions are minimized. In this context, Life-cycle Assessment (LCA) is an excellent tool to record, analyze and critically review the environmental impact of a process. In order to investigate the environmental hotspots, the authors have performed LCA of an auto-parts manufacturing industry in Pakistan by using a unique gate-to-gate approach. ReCiPe Midpoint impact assessment method was utilized to investigate the effects of manufacturing and transportation related emissions of the monthly produce on climate change, fossil depletion, ionizing radiation and human toxicity. Furthermore, the authors discuss three scenarios, which include current state, optimized future state and an energy mix involving hydropower and photovoltaic generation. The results helped in developing a comprehensive framework for green manufacturing which suggests that the prerequisite of a green manufacturing process is an optimized process flow, which significantly reduces the environmental emissions up to 24%. Moreover, the use of photovoltaic cells results in 54% reduction, thus indicating that conventional hydropower systems in developing countries should be mixed with solar power to reduce the environmental burden. A detailed green manufacturing framework based on LCA is proposed by the authors to enhance the functionality and to improvise the carbon burden of the manufacturing sector of Pakistan.

Keywords Life-cycle assessment, Green manufacturing, Sustainability, Climate change, Framework

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1 Introduction

Mankind has always strived to achieve sustainability in its actions, from the invention of wheel to the development of steam engine; every single invention was supposed to ease the lives of people with the idea of further development. As the twenty-first century set in, manufacturing sector went through radical changes and digitalization of processes began to take place. Unfortunately, the rapid growth of industries to satiate the demands of ever-increasing competition took their toll on the climate and the world is now facing the biggest crisis in its history in the form of climate change. However, all is not lost, and mankind can still curb damages of climate change by taking necessary steps to ensure meticulous analysis of every action, process or cycle from the lens of environmental betterment. Recyclable products can be used and in cases where products cannot be recycled, they should be manufactured in such a manner that their useful life is prolonged, without any detrimental impact on the environment. With the depleting natural resources and ever-increasing demand for high value product, the manufacturing paradigm has seen numerous changes in the recent years and there has been a trend shift towards modern manufacturing processes that are commercially viable and environment friendly. Sustainability is of paramount importance in the modern world and its benefits include improved resource efficiency, prolonged product life, as well as innovative and reconfigured value chains.

The Inter-Governmental Panel on Climate Change, comprising of more than 1300 scientists from the United States and other countries, forecasts a temperature rise of 0.5–4.5 °C over the next years [1]. Life-cycle Assessment (LCA) is a very handy tool to cater eco-efficiency perspective and evaluate the sustainability and environmental impact of a manufactured products. It is widely used for comprehensive assessment of environmental aspects and impacts that encompasses the entire life-cycle of a product; commencing from raw material acquisition and processing to the final product delivery till its disposal. It views manufactured products from their life-cycle perspective that proves vital in avoidance of several problems. As per ISO 14040:2006, LCA framework is summarized as definition of goal and scope, life-cycle inventory analysis, life-cycle impact assessment (LCIA), life-cycle implementation, reporting and critical review, and limitations [2].

ISO 14045 [3] defines LCA as a quantitative procedure to evaluate and measure the environment deterrents involved in the life-cycle of a product, process, service etc. The holistic view of life-cycle includes extraction of raw materials, transportation, processing, manufacturing, packaging, storing, distribution, usage, maintenance, repair and disposal/recycle [4]. In policy development and consolidation, regulatory authorities have used LCA as it influences the business and social decisions, waste management being one good example [5]. This, in turn, has led to the *cradle-to-grave concept* of product stewardship as a business decision mechanism, whereby responsibility is accepted for the environmental practices upstream (suppliers) and downstream (customers or clients) of a company's activity [6]. The unique feature of LCA is that it focuses on products, product systems and services in a life-cycle perspective such that the nature of impacts can be modelled in a systematic manner to quantify environmental impacts. Step-by-step phases of LCA are presented in Fig. 1. One can stipulate the changes to be made by identifying the caveats as it often helps in gap analysis. Tang et al. [7] developed an optimization framework after integrating LCA in the design phase of the product, using energy and material consumption models. Similarly, Campatelli et al. [8] presented a methodology that encompasses all the energy flows in a component's life-cycle, which was later analysed on a wire arc additive manufacturing process, resulting in significant energy saving and positive environmental gains. Duflou et al. [9] proposed a LCA-based framework for evaluating greenhouse gas (GHG) emissions and carbon footprints.

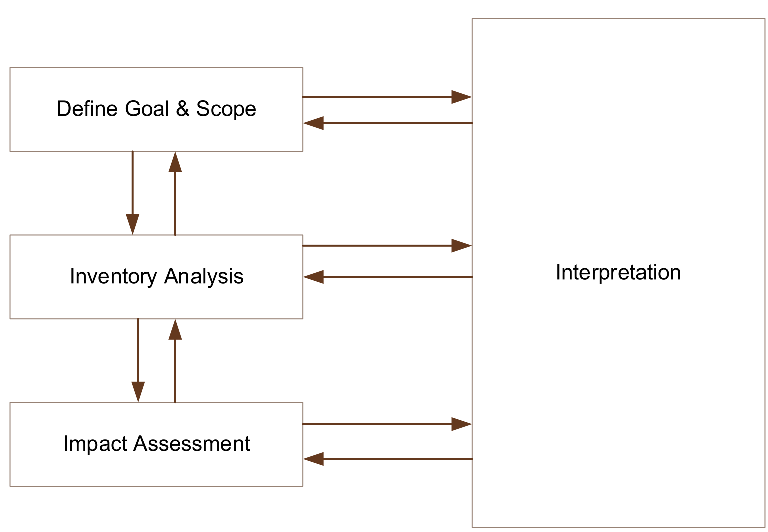

Fig. 1 Phases of LCA

LCA approach helps in gauging the environmental impact of the manufacturing or service process, but there is requirement of a comprehensive implementation framework that helps in adoption of green techniques to ensure environmentally conscious manufacturing. Deif [10] developed a framework for implementing green manufacturing that consisted of four main phases—problem definition, problem identification, implementation of green manufacturing and sustaining green manufacturing for continuous improvement. It utilized green Value Stream Mapping (VSM) but did not approach the implementation from an LCA perspective. Digalwar et al. [11] presented a roadmap for green manufacturing implementation in Indian industries using an Interpretive Structural Modelling approach, and concluded that top management commitment and employee empowerment were essential for successful green manufacturing. Toke and Kalpande [12] have discussed key enablers to green manufacturing implementation and conclude that green packing of products, lean manufacturing implementation and top management commitment are strong enablers for the implementation of green manufacturing. Zhang et al. [13] developed a comprehensive framework for implementing green manufacturing in marine equipment manufacturing industry that is divided into product life-cycle and implementation phases; however the developed framework, despite being thorough and comprehensive; seems too complicated to be implemented in other manufacturing industries. Therefore, to the best of the authors' knowledge after conducting a literature review, there is requirement of a comprehensive and simplistic green manufacturing implementation framework that can be easily applied in industries, regardless of their size, in order to ensure environmentally conscious manufacturing practices with minimized carbon footprint.

The paper is structured as follows: Sect. 2 discusses applications of LCA principles on a manufacturing firm, Sect. 3 discusses the results and develops three scenarios for attaining optimum green benefits, Sect. 4 utilizes the results of the case study and process improvement approaches present in the literature to develop a comprehensive, yet simplistic green manufacturing implementation framework, whereas Sect. 5 concludes the research, discusses the limitations and gives directions for future research.

2 Methodology

The authors performed LCA of a brake pad, a vital component in automotive braking systems having a supposed name CS made by an auto-parts manufacturing firm (RR Group) located in the outskirts of Lahore, Punjab Pakistan. The organization has been one of the most coveted Tier-2 suppliers for Atlas Honda in Pakistan and have taken it upon themselves to improve the environmental performance of the manufacturing facility. Being a medium scale manufacturing firm with limited resources at their disposal, the authors selected CS product after consulting the field engineer. Field data was collected in the presence of production personnel, which included material specifications, energy consumption, manufacturing time, and the transportation distances. The authors used OpenLCA software tool and employed Ecoinvent 3.3 database. The four distinct phases of LCA assessment include:

2.1 Goal and scope

LCA activity starts with an explicit definition of goals and scope of the study that is being carried out. The aforementioned carries significant importance in ISO standards [2]; the document comprising of goal and scope, therefore, includes technical details that guide subsequent work. The goal of this case study is to analyze the manufacturing processes performed on product CS at each succeeding step. This case study involves a unique gate-to-gate approach of the product CS.

2.1.1 Functional unit

It precisely defines the entities under study and quantifies the delivered services, while interrelating inputs and outputs. It states the reference property for evaluating environmental impacts. In this case study, the functional unit was the number of units produced by the manufacturing facility of a single product monthly i.e., 30,000 pieces of the CS product are manufactured each month.

2.1.2 System boundaries

The authors stipulated the limitations of the processes along with their inclusivity status. In this scenario, the authors used a gate-to-gate approach in which the data from raw material supplier to the warehouse of the customer was considered. The system boundaries are shown in Fig. 2.

2.1.3 Perspective

The authors selected a consequential approach [14] in this study as the goal was to determine the burdens put on the environment by manufacturing the CS product. As the RR Group works in a highly competitive environment, therefore monthly production demands have considerable variations.

2.1.4 Impact categories

The impact categories assessed during the study include:

1) Agricultural land occupation ($m^{2*}a$)
2) Climate change (kg CO_2 eq)

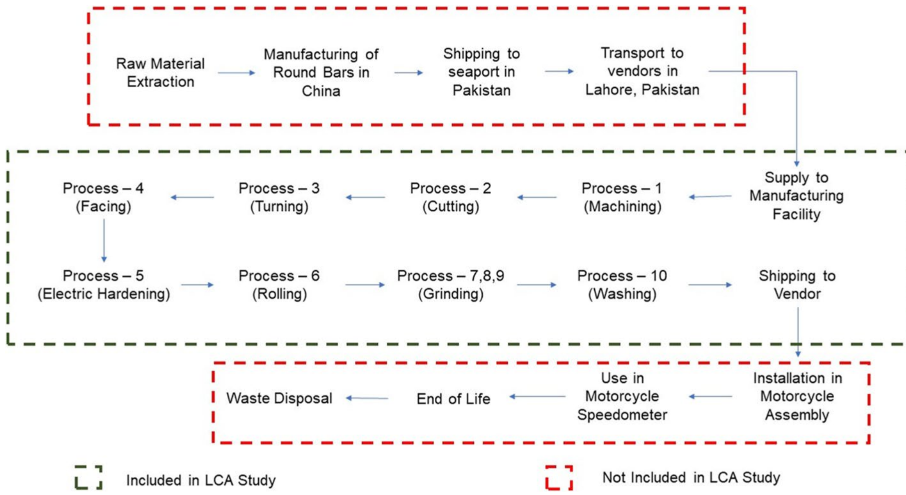

Fig. 2 System boundaries for LCA study

3) Fossil depletion (kg oil-eq)
4) Freshwater ecotoxicity (kg 1,4-dichlorobenzene (dcb)-eq)
5) Freshwater eutrophication (kg P eq)
6) Human toxicity (kg 1,4-dcb-eq)
7) Ionising radiation (kg U 235 eq)
8) Marine ecotoxicity (kg 1,4-dcb-eq)
9) Marine eutrophication (kg N eq)
10) Metal depletion (kg Fe eq)
11) Natural land transformation (m^2)
12) Ozone depletion (kg CFC 11-eq)
13) Particulate matter formation (kg PM_{10})
14) Photochemical oxidant formation (kg NMVOC)
15) Terrestrial acidification (kg SO_2 eq)
16) Terrestrial ecotoxicity (kg 1,4-DCB eq)
17) Urban land occupation ($m^{2*}a$)
18) Water depletion (m^3)

2.2 Life-cycle inventory

In this process, the entire inventory of system in-flows and out-flows from an external agency were observed, using a flow model. The model summarizes the whole supply/value chain and life-cycle inventory analysis was carried out using Ecoinvent 3.3 database in OpenLCA software.

2.3 LCIA

After Life-cycle Inventory was successfully prepared, the flow results were evaluated based on their environmental performance by selecting the impact categories and their relevant category indicators, which in turn provided a measurement of the environmental impacts of all the processes. In the present case, the authors used ReCiPe 2016 Midpoint method for LCIA using the hierarchist approach. This method is combination of problem based and damage-based orientation; and interprets the environmental emissions and resource utilization of any product during its life-cycle into measurable or countable score by using characterization factors. There are two types of characterization factors defined in this method for midpoint and endpoint indicators. Midpoint characterization factors lie in between emissions and damage and correspond to eighteen indicators defined in recipe while endpoint factors relate to the three protection areas of human health, ecosystem quality and resource scarcity. This method determines midpoint and endpoint indicators, and analysis at both levels can be performed. Midpoint characterization method is implicit as compared to endpoint method because of its stronger relationship to environmental flows. Endpoint characterization, however, provides better environment related information but it is uncertain as compared to midpoint [15], therefore the authors chose the midpoint method in this study.

2.4 Interpretation

LCA is a systematic tool to identify, quantify, check and evaluate the information from the results of preceding phases [16]. The outcome is usually a set of conclusions and recommendations that act as guidelines. According to ISO 14040:2006 [2]. the interpretation should include (1) issue identification as per LCI and LCIA; (2) comprehensive study evaluation for completeness, sensitivity and consistency; and (3) conclusions, limitations and recommendations. After conducting the study and analyzing the results, the authors put forward scenario of mixed energy consumption, and postulated that production optimization forms a basic tenet of improvement in environmental performance.

3 Results

3.1 Scenario 1 – current state

The details of the processes involved from gate-to-gate assessment are in Table 1. It can be seen that there are 10 manufacturing processes that consume electricity, whereas there are two transportation related processes that involve shipping of raw material and the final product. In the selected manufacturing facility, 30,000 products were produced in 26 days and the details of energy consumed are provided. An assumption was made that the 15% of material goes to waste in the manufacturing process. The graph encapsulating the emissions is given in Fig. 3, and it can be clearly seen that the electricity has a lion's share in the emissions, mainly due to the fact that Pakistan is reliant on hydropower, and its transmission and distribution system is based on conventional methods. The monthly emissions from energy and auxiliary inputs, heat from machines, in the realm of mild steel metalworking, processes such as lathe machining generate significant emissions that contributed to the impact categories, whereas transportation related emissions had minimum impacts, owing to the fact that the transport distances were quite short and manufacturing facility was equidistant from the material supplying vendor and the client. Table 2 lists impact categories for current state of processes and supplementary file presents a comprehensive display of the impact assessment findings derived from OpenLCA software, providing a detailed analysis for reference.

Table 1 Current state of processes for producing 30,000 pieces in 26 days

Sr. #	Process	Distance/ Electricity Consumption	Units
1	Distance Travelled From Vendor to Factory	19.7	km
2	Machining	1239	kWh
3	Key Cutting	545	kWh
4	Diameter Turning	108	kWh
5	Facing	181	kWh
6	Tip Hardening	48	kWh
7	Thread Rolling	218	kWh
8	Multi Dia. Grinding	781	kWh
9	Ø9mm Final Grinding	836	kWh
10	Ø5.5 mm Final Grinding	823	kWh
11	Quality Inspection	41	kWh
12	Washing	0	kWh
13	Packing	0	kWh
14	Distance Travelled from Factory to Client	20.1	km

3.2 Scenario 2 – proposed future state

Considering the process flow that was incumbent upon inventory of 600 pieces that was forwarded to each workstation, the authors employed the use of lean manufacturing technique of first-in-first-out to minimize the inventory, make the process swift and reduce the work time. By the application of lean principles, the 30,000 pieces that were produced in 26 days were now being produced in 21 days, so there was a ~19% reduction in the manufacturing time. Moreover, the previously 15%

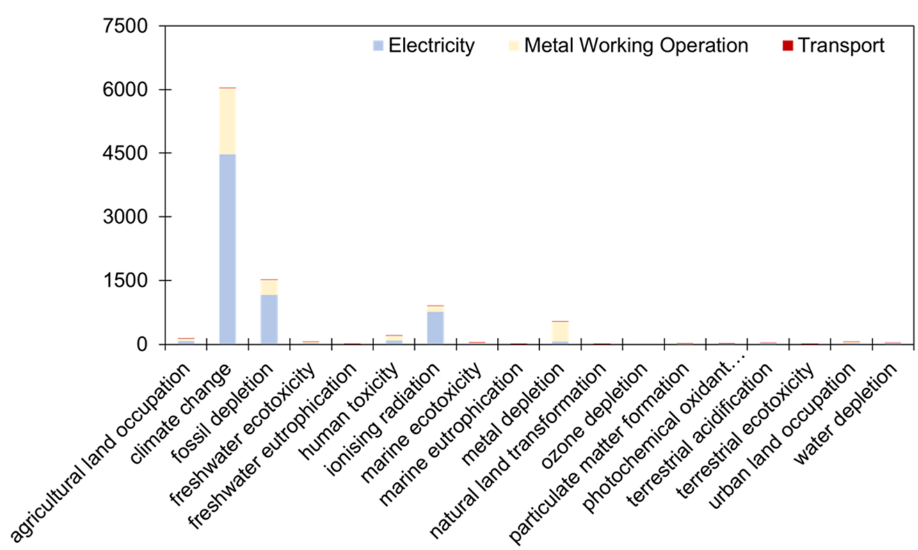

Fig. 3 Comparison of major emissions from electricity, metal working and transportation for the current state of processes

Table 2 Impact categories for current state of processes

Impact categories	Electricity	Metal working operation	Transport
Agricultural land occupation (m^2*a)	74.57421	53.038637	0.194007
Climate change (kg CO_2-Eq)	4470.284	1562.2066	12.57065
Fossil depletion (kg oil-Eq)	1167.062	337.85844	4.196996
Freshwater ecotoxicity (kg 1,4-DCB-Eq)	29.46085	16.593489	0.032669
Freshwater eutrophication (kg P-Eq)	1.948682	0.5572558	0.001124
Human toxicity (kg 1,4-DCB-Eq)	88.32578	113.67703	0.268173
Ionizing radiation (kg U235-Eq)	762.257	139.76136	0.339506
Marine ecotoxicity (kg 1,4-DCB-Eq)	23.28696	13.29683	0.030726
Marine eutrophication (kg N-Eq)	4.155308	1.5560712	0.027641
Metal depletion (kg Fe-Eq)	59.39835	469.74482	0.694572
Natural land transformation (m^2)	0.536516	0.253732	0.003314
Ozone depletion (kg CFC-11-Eq)	0.000248	5.39E-05	7.74E-07
Particulate matter formation (kg PM_{10})	9.719171	3.2062944	0.027305
Photochemical oxidant formation (kg NMVOC)	12.04497	4.4091374	0.088187
Terrestrial acidification (kg SO_2-Eq)	22.6582	6.8655411	0.050607
Terrestrial ecotoxicity (kg 1,4-DCB-Eq)	0.212418	0.1029759	0.002075
Urban land occupation (m^2*a)	28.33491	26.256409	0.575822
Water depletion (m^3)	18.09801	11.770945	0.014022

wastage in the manufacturing process was reduced to 8% after careful analysis of the production line which led to the identification of processes that generated too much metal swarf. In addition, high usage of electricity, which contributes the most to environmental impacted emissions, was minimized by improving the power effectiveness of the installed machinery. It was observed that the current power factor of the supplied electricity was around 0.8, thus the authors suggested a power factor improvement electrical panel, which elevated the power factor to 0.9 and on some occasions, 0.95. Similarly, it was suggested that the application of Total Preventive Maintenance would result in improved performance of the machinery. In line with the aforementioned, the changes observed in the impact categories are given in Table 3.

The results are further depicted in Fig. 4 and it was seen that the impact values considerably reduced (~ 30%) by reducing the manufacturing time using the principles of lean manufacturing, whereas the emissions from metal working operation and transport saw a minimal decrease in the values, mostly due to the fact that the wastage of 15% during manufacturing process was reduced to 8%.

It can be seen that the emissions from electrical power serve as major contributor towards the global warming emissions, followed by human non-carcinogenic toxicity. It was initially expected that transportation would have the most impact on the environmental performance, but the short distances from supplier and vendor suggest that it had a minimal impact on the emissions.

3.3 Scenario 3 – solar power

In line with the results of environmental impacts, it is imperative to move to a renewable energy resource that reduces the dependence on national grid. Therefore, solar power is an economically viable option in the market and the results of solar power-based manufacturing operation are given in Table 4.

The results suggest that the emissions from electricity see a drastic drop upon use of solar power, as opposed to the conventional electricity generation process. However, the recorded values of human non-carcinogenic toxicity in case of metal working operation are almost thrice in comparison to the case of photovoltaic electricity generation, as shown in Fig. 5.

3.4 Discussion

A comparison of the three scenarios is presented in Fig. 6, in which it is evident that the combined implementation of production optimization principles and an organizational policy of renewable-energy based electricity consumption gives a major boost towards improved environmental performance.

The implementation of production optimization principles results in approximately 24% reduction in the environmentally detrimental GHG emissions, whereas the solar-powered manufacturing process provides a considerable reduction of 54%. However, the non-carcinogenic toxicity due to solar power is almost 34% higher than the optimized production process. This increase can be attributed to the fact that the commercially available

Table 3 Impact categories for manufacture of 30,000 pieces using production optimization principles and improving the power factor

Impact categories	Electricity	Metal working operation	Transport
Agricultural land occupation (m^2*a)	63.38808	58.80371	0.164906214
Climate change (kg CO_2-Eq)	3799.741	1732.012	10.68505398
Fossil depletion (kg oil-Eq)	992.0025	374.5822	3.567446537
Freshwater ecotoxicity (kg 1,4-DCB-Eq)	25.04172	18.39713	0.027768411
Freshwater eutrophication (kg P-Eq)	1.656379	0.617827	0.000955
Human toxicity (kg 1,4-DCB-Eq)	75.07692	126.0332	0.227947093
Ionising radiation (kg U235-Eq)	647.9185	154.9528	0.288579863
Marine ecotoxicity (kg 1,4-DCB-Eq)	19.79392	14.74214	0.026117211
Marine eutrophication (kg N-Eq)	3.532012	1.725209	0.023495231
Metal depletion (kg Fe-Eq)	50.48859	520.804	0.5903859
Natural land transformation (m^2)	0.456038	0.281312	0.0028165
Ozone depletion (kg CFC-11-Eq)	0.000211	5.98E-05	6.58301E-07
Particulate matter formation (kg PM_{10})	8.261295	3.554805	0.023209333
Photochemical oxidant formation (kg NMVOC)	10.23822	4.888392	0.074958577
Terrestrial acidification (kg SO_2-Eq)	19.25947	7.611796	0.04301637
Terrestrial ecotoxicity (kg 1,4-DCB-Eq)	0.180555	0.114169	0.001763759
Urban land occupation (m^2*a)	24.08468	29.11037	0.489448739
Water depletion (m^3)	15.38331	13.05039	0.011918386

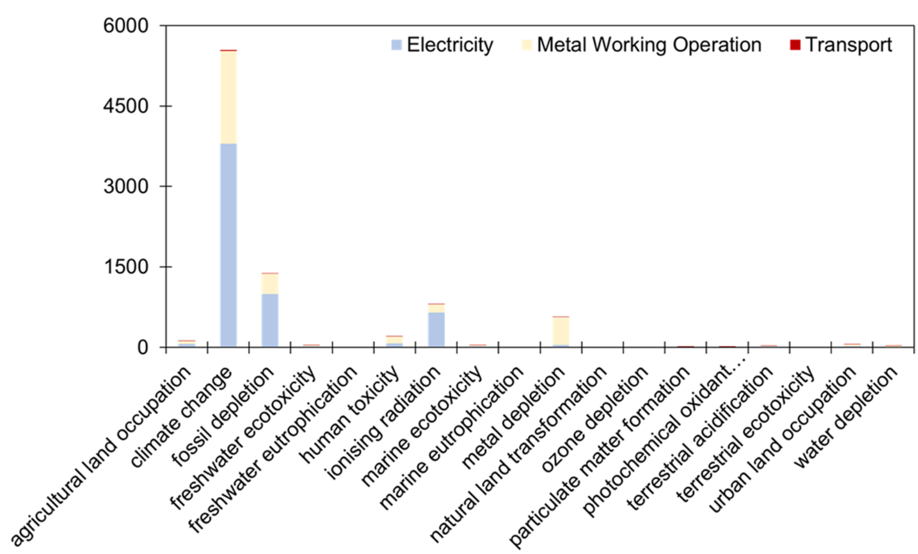

Fig. 4 Comparison of major emissions from electricity, metal working and transportation for the future tentative state of processes as per lean manufacturing principles

perovskite photovoltaic cells include lead content that is a strong enabler of toxicity and effect is more pronounced in case of terrestrial eco-toxicity.

4 A framework for green manufacturing implementation

With the changing local and global dynamics, it is necessary to integrate operational and environmental facets to improve the eco-efficiency of the system. Srivastava [17] remarked that the adoption of green practices in a supply chain is essential to improve the environmental performance, and carries immense capability to leverage improved economic performance. From a practitioner's perspective Mollenkopf et al. [18] have asserted that a systems approach may be utilized that combines the concepts of lean manufacturing and green manufacturing, since the adoption of former complements the environmentally benign manufacturing, whereas the latter

Table 4 Impact categories for manufacture of 30,000 pieces using production optimization principles and improving the power factor

Impact categories	Electricity	Metal working operation	Transport
Agricultural land occupation (m^2*a)	36.709069	53.0386367	0.19400731
Climate change (kg CO_2-Eq)	685.98713	1562.20664	12.5706517
Fossil depletion (kg oil-Eq)	167.96525	337.858443	4.19699593
Freshwater ecotoxicity (kg 1,4-DCB-Eq)	12.107575	16.5934892	0.03266872
Freshwater eutrophication (kg P-Eq)	0.5682917	0.55725583	0.00112353
Human toxicity (kg 1,4-DCB-Eq)	85.805505	113.677027	0.26817305
Ionising radiation (kg U235-Eq)	71.498209	139.761361	0.33950572
Marine ecotoxicity (kg 1,4-DCB-Eq)	10.858419	13.2968304	0.03072613
Marine eutrophication (kg N-Eq)	0.8063947	1.55607123	0.02764145
Metal depletion (kg Fe-Eq)	237.88404	469.744824	0.69457165
Natural land transformation (m^2)	0.0880356	0.25373197	0.00331353
Ozone depletion (kg CFC-11-Eq)	0.0001138	5.3913E-05	7.7447E-07
Particulate matter formation (kg PM_{10})	1.656864	3.2062944	0.0273051
Photochemical oxidant formation (kg NMVOC)	2.5791287	4.40913743	0.08818656
Terrestrial acidification (kg SO_2-Eq)	4.2314619	6.8655411	0.05060749
Terrestrial ecotoxicity (kg 1,4-DCB-Eq)	1.1094719	0.1029759	0.00207501
Urban land occupation (m^2*a)	6.7603835	26.2564092	0.57582205
Water depletion (m^3)	3.0150938	11.7709445	0.01402163

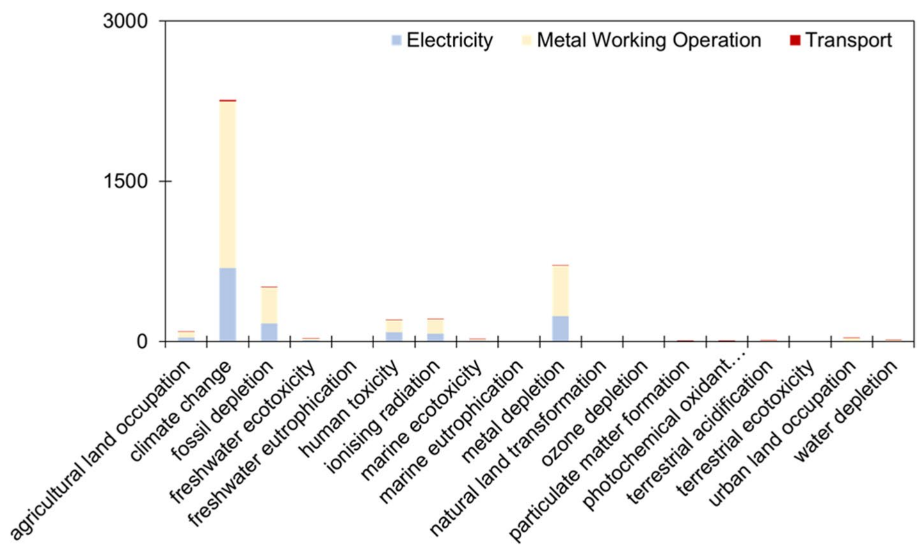

Fig. 5 Comparison of major emissions from solar-electricity, metal working and transportation for the future tentative state of processes as per lean manufacturing principles

improves the economic performance of manufacturing and supply chains. However, all other process improvement methodologies, the holistic implementation of environmentally benign manufacturing practices is a gradual process and requires patience and commitment, since a few strategic decisions may result in increased operational costs. The narrative of wastage reduction was further validated by Deif [10] who asserted that supply chain performance is increased by adopting green practices since it reduces the production time and increases the operational and process efficiency.

The environment is a function of our actions, and for its betterment green practices are required to be effectively implemented. The supply chain efficacy can be increased by using lean & green approach, along with customer satisfaction and high product/service quality [19]. The greening of the supply chain depends upon product life-cycle influence, the operational life-cycle,

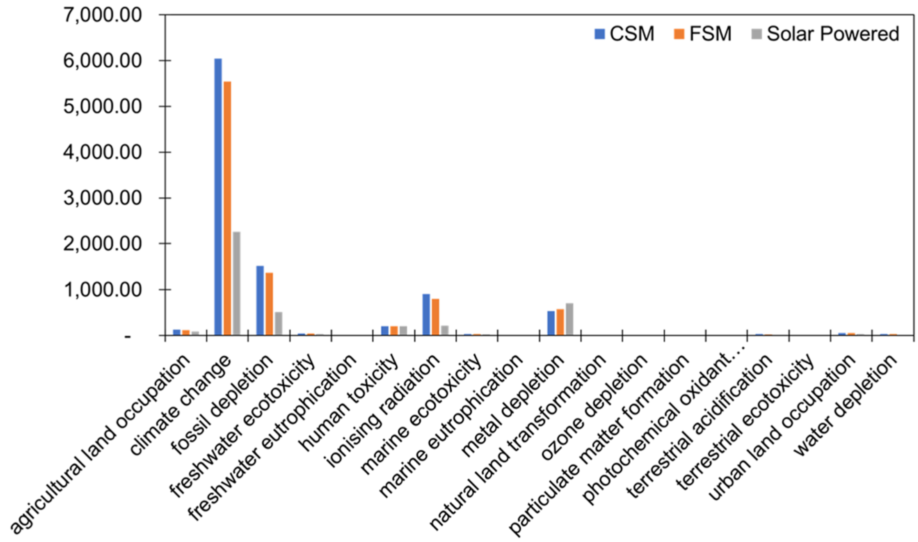

Fig. 6 Comparison of current state scenario, production-optimization based future state scenario and solar-powered manufacturing process

environmentally influential organizational practices and organizational performance requirements [20]. Lee [21] remarked that adopting green practices depends heavily upon the willingness of buyer and seller, making it an ethical choice. Furthermore, the green practices are found to have positive influence on business performance [22]. Environmental Management System helps in increasing the environmental performance of the supply chain by requiring all the stakeholders in the supply chain to minimize their wastes and move towards greener energy solutions [23]. Moreover, it also helps managers to assign resources towards the ecological narrative more effectively. It can be seen from literature that it is essential to include environmentally friendly practices in manufacturing to improve eco-performance [24]. Building upon the suggestion of literature [25] the products should be viewed from a life-cycle perspective for improved environmental performance.

The implementation of green manufacturing should be viewed as a process improvement approach, rather than a standalone implementation of a policy/standard. There are numerous process improvement frameworks present in the literature which include lean six sigma, balanced scorecards, Taguchi Design of Experiments, Quality Management System, etc. The approach of Lean Six Sigma comes in quite handy for process improvement, as it offers a holistic perspective and is an organization-wide approach to ensure operational excellence. The integrated tools of VSM and DMAIC (Define, Measure, Analyze, Improve, Control) not only help in identifying the areas for improvement, but provide a framework for improving the processes as well. Therefore, the authors present the following framework for implementing green manufacturing which constitutes four phases: Define, Measure, Analysis & Improvement, and Control & Sustain.

4.1 Phase 1 – define goals

In the first phase of green manufacturing, it is necessary to clearly define the issue i.e., reduction of environmentally detrimental emissions from the manufacturing process. In this context, it is necessary that there should be irrevocable support and commitment from top management; therefore, strategic decisions should be made to give environmental performance the same importance as that of economic performance. Once a consensus is reached, a green team should be formed that is responsible for enacting the vision of the top management and should be cross functional in its innate nature i.e., it should include personnel from production, maintenance, operations, quality, management departments etc.

4.2 Phase 2 – measuring the green performance

In order to measure the green performance, it is imperative that a few lean manufacturing practices should be implemented first so that the production process is made fast and optimized. Toke and Kalpande [12] have suggested that lean implementation can act as a strong lever for green manufacturing implementation, and this idea is supported by Duarte and Cruz Machado [25]. VSM approach is an excellent opportunity to remove wastes from the manufacturing process, whereas the life-cycle assessment is an obvious choice for measuring the environmental performance. The impact assessment can be carried out using numerous methods such as:

Eco indicator 99—It utilizes end-point LCA method by applying a methodology focused on damage quantification. It lays importance to areas such as health, resources and ecosystem, by modelling the damage on these areas. An upgrade on Eco-Indicator 95, this widely used endpoint assessment method applies a top-down approach to determine the damage sources to defined areas of importance.

CML 2001—This method utilizes a problem-oriented approach trying to locate a midpoint between emissions and damages. This midpoint LCA tool includes baseline and non-baseline categories, with the baseline categories frequently utilized in LCAs.

Impact 2002+—While being a midpoint method, it also utilizes damage-oriented methodology to combine LCA inventory results to 4 damage categories. It does so by using 14 midpoint categories and links them together by cause and effect. Further characterization is done by defining flows and interventions with each linked to quantifiable endpoints.

Recipe 2008—A combination of midpoint and endpoint LCA method, it is utilized widely for comprehensive environmental impact of a product over its life time. By defining two types of characterization factors, the method outputs environmental emissions and resource utilization of a product. It also combines damage and problem-based orientations. 18 midpoint indicators are defined corresponding to damages while 3 endpoints are defined for health, ecosystem quality and resource scarcity respectively. So, a flexibility is achieved between the implicit midpoint and endpoint analyses.

Recipe 2016—An updated version of the aforementioned Recipe 2008, it utilizes the same principles of combination of midpoint and endpoint methods. It is the most prevalent LCA method in research and industry, due to its combination approach and global factors inclusivity. While Recipe 2008 used European standards, this version adapts to global indicators, leading to its widespread utilization and success.

Impact world+—Another global combination method, it also utilizes midpoint and endpoint life-cycle assessment technique by developing and combining methods observed in Impact 2002+, the Land Use/Cover Area frame Survey and Environmental Design of industrial products. It also uses global characterizations, similar to Recipe 2016 and offers the added benefit of four levels of product life-cycle assessment of emissions and resource utilization: global default, continental default, country default and native resolutions. It also reduces the uncertainty level that is often encountered in other life-cycle assessment methods.

Furthermore, the following impact categories are present in the results and literature that can be considered during the measurement of green performance: fine particulate matter formation (kg PM_{10}) fossil resource scarcity (kg oil eq.), freshwater eco-toxicity (kg 1,4-DCB), freshwater eutrophication (kg P eq.), global warming (kg CO_2 eq.), human carcinogenic toxicity (kg 1,4-DCB), human non-carcinogenic toxicity (kg 1,4-DCB), ionizing radiation (kBq Co-60 eq.), land use (m^{2}*a crop), marine eco-toxicity (kg 1,4-DCB), marine eutrophication (kg N eq.), mineral resource scarcity (kg Cu eq.), ozone formation, human health (kg NOx eq.), terrestrial ecosystems (kg NO_x eq.), stratospheric ozone depletion (kg CFC11 eq.), terrestrial acidification (kg SO_2 eq.), terrestrial eco-toxicity (kg 1,4-DCB), and water consumption (m^3). In line with the manufacturing sector, managerial personnel can select the most pertinent emission/impact for articulating green and environmentally conscious manufacturing.

4.3 Phase 3 – analysing and improving green performance

After measuring the green performance, the recordings need to be checked for validity first by using a statistical tool such as ANOVA to determine the optimal value of certain major parameters. It also helps in authenticating the recorded values hypothesis rejection and selection approach. Once the measurements are analyzed, the improvement process follows the pattern of VSM where the caveats are identified, and a future state map is drafted for process improvement. Variables such as climate change, ozone depletion, terrestrial acidification, fresh water eutrophication, marine eutrophication, human toxicity, photochemical oxidation, particulate matter formation, terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, ionizing radiation, agriculture land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, fossil resource depletion, etc. can be analyzed and improvement targets can be set.

4.4 Phase 4 – control and sustain

It is necessary to consider that green manufacturing implementation is an iterative practice and requires continuous efforts from all the stakeholders. Therefore, a continuous improvement plan is necessary to sustain the results and it is incumbent upon the top management to ensure that the workers are committed and empowered.

Table 5 suggests that green manufacturing implementation consists of four phases that are subdivided into a cumulative of ten processes. The developed framework has been applied to a manufacturing industry via simulation to achieve interesting results.

Table 5 Steps & phases of green manufacturing implementation framework

Phase	Steps for improvement	Reference from previous literature
Phase 1—define goals	1. Commitment from top management	[11, 26, 27]
	2. Building a green team	[12, 28]
Phase 2 – Measuring green performance	3. Implementation of lean manufacturing principles	[25, 29]
	4. Value stream mapping of the entire process	
	5. Life-cycle assessment of the process	[30, 31]
	6. Life-cycle impact assessment	
Phase 3 – Analysis of results & improving green performance	7. Authentication of recorded values using ANOVA	[31–33]
	8. Drafting future state map for improved performance	[25, 34]
	9. Use of renewable energy resources	[35, 36]
Phase 4 – control & sustain	10. Continuous Improvement	[33, 37]

It is pertinent to mention that the successful implementation of green manufacturing principles is dependent upon the optimized production process with reduced cycle and lead times, therefore the VSM approach is essential in articulating the green manufacturing principles. With the development in area of life-cycle assessment, new impact assessment methods are being introduced and old methods are being updated for performing comprehensive and precise analysis of products. There are different LCIA methods available for performing LCA and there are not any fixed criteria for choosing a specific method for performing the assessment analysis. Selection of the best suitable method depends upon many factors. Main factors for selecting best suitable assessment method includes area of research, product life-cycle, type of impact (human health, aquatic or ecosystem) produced and operational pattern assumed. A graphical representation of the framework is shown in Fig. 7.

5 Conclusions

In this research work, the authors have undertaken LCA approach using ReCiPe Midpoint analysis to improve the environmental performance of a manufacturing facility. The metal parts manufacturer was subjected to a holistic production optimization in which the process time and cycle time were reduced, to see a 24% improvement in the environmental performance. It was further improved by the implementation of solar power by ~ 40% (cumulatively 54% from the current state of processes) and the climate change potential was drastically reduced. Due to minimal transportation distances, the transport related emissions were of negligible importance whereas electric supply accounted for most of the emissions. However, it was observed that even though adoption of solar power helps in reducing the GHG emissions, the toxicity potential increases due to the use of lead and cadmium in the production of photovoltaic cells. The results of the life-cycle assessment study helped in developing an implementation framework for green manufacturing which is centered upon the application of lean manufacturing principles and LCA approach. The developed framework is divided into four phases and ten steps using process improvement DMAIC methodology; and is an easy-to-adopt tool for managerial personnel to implement environmentally-conscious manufacturing approaches in their organization.

The authors have used the ReCiPe midpoint approach using a hierarchist perspective, however endpoint methodology would provide a more structured and informed set of results. The use of egalitarian perspective provides a pessimistic approach towards the life-cycle assessment by considering the worst-case scenario, and it is extremely useful to provide data for national policies. In addition to that, the authors have confined to the gate-to-gate approach and have not considered the environmental impacts of the metal ore extraction, processing and transportation – as the aim was to assess the environmental impact of the metal-part manufacturing process. A complete cradle-to-grave study would yield interesting results and the emissions from metal extraction and processing may dominate the emissions from electricity or transportation. The authors assumed 15% wastage in formation during the entire production process, and was simulated to be 8% after implementation of production optimization principles – however a longitudinal validation is required. And finally, the developed framework needs to be implemented on a manufacturing industry for cross sectional validation.

In future, a cradle-to-gate approach can be used to undertake the sustainability assessment of a

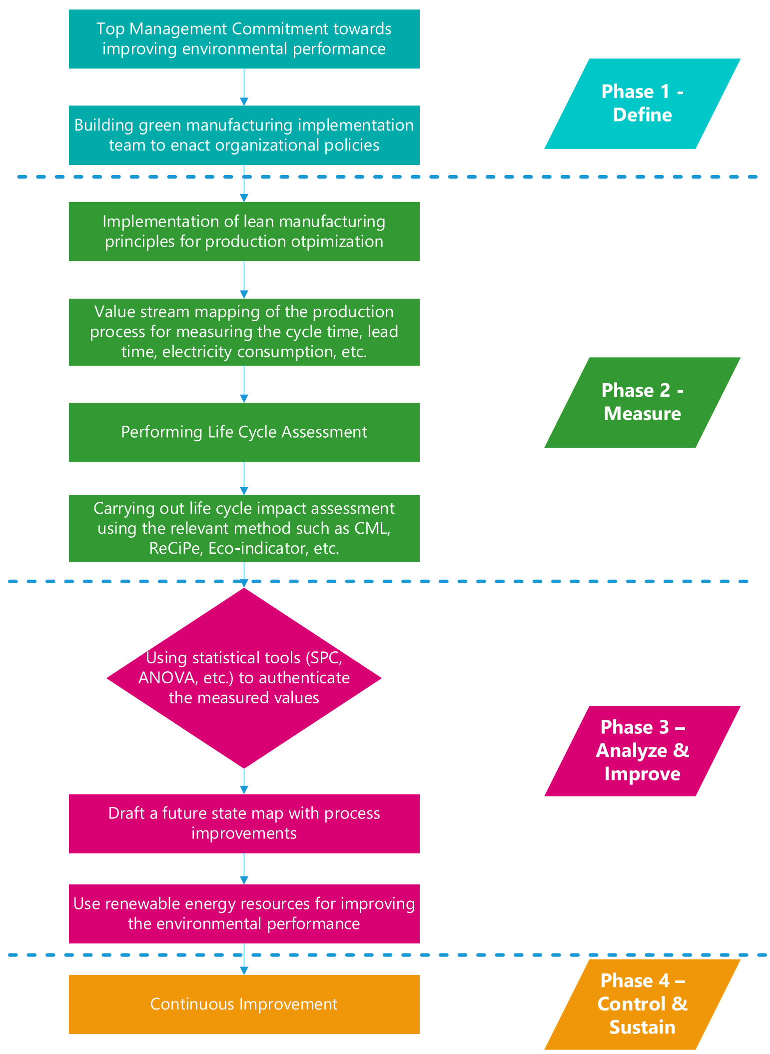

Fig. 7 Green manufacturing implementation framework

manufacturing process, including economic and social dimensions, and implementing green manufacturing. Instead of causal allocation, physical or economic allocation can be carried out to achieve better results.

Supplementary Information

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Supplementary Material 1.

Authors' contributions

All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated during the current LCA study are available from the corresponding author on reasonable request. The data collected from the manufacturing industry is mentioned in Table 1. Based on the industrial data, LCA is done to calculate the impacts.

Declarations

Competing interests

The authors hereby declare no potential conflict of interest.

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