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Greening the future: identifying and mitigating environmental hotspots in the MSME sector - a wall mixer case study

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ABSTRACT

In response to concerns about depleting natural resources, organisations are developing eco-friendly products and services. This study examines the role of manufacturing industries and services in sustainable resource utilisation, focusing on the Micro, Small, Medium Enterprises (MSME) sector, a significant contributor to global Gross Domestic Product (GDP). Using Life Cycle Assessment (LCA) methodology, the research identifies hotspots within the production processes of three companies manufacturing bathroom fittings, specifically the 'Wall mixer' component used in households and hotels. The study calculates In response to concerns about depleting natural resources, organisations are developing eco-friendly products and services. This study examines the role of manufacturing industries and services in sustainable resource utilisation, focusing on the MSME sector, a significant contributor to global GDP. Using Life Cycle Assessment (LCA) methodology, the research identifies hotspots within the production processes of three companies manufacturing bathroom fittings, specifically the 'Wall mixer' component used in households and hotels. The study calculates CO_2 equivalents for each phase of the product lifecycle, identifying average gate-to-gate process values across the companies. This comparison reveals specific hotspots, with a significant one identified, leading to recommendations for industries to prioritise this issue for immediate energy savings. The primary focus is to establish an initial benchmarking system to reduce CO_2 equivalents in cradle-to-gate or gate-to-gate systems. Implementing these measures is expected to reduce the carbon footprint, energy consumption, and raw material usage, ultimately enhancing profitability for the three companies. equivalents for each phase of the product lifecycle, identifying average gate-to-gate process values across the companies. This comparison reveals specific hotspots, with a significant one identified, leading to recommendations for industries to prioritise this issue for immediate energy savings. The primary focus is to establish an initial benchmarking system to reduce CO_2 equivalents in cradle-to-gate or gate-to-gate systems. Implementing these measures is expected to reduce the carbon footprint, energy consumption, and raw material usage, ultimately enhancing profitability for the three companies.

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Sustainability; MSME's; carbon dioxide equivalent; greenhouse gas emissions (GHGs); hotspot analysis

1. Introduction

Currently, the manufacturing sector is witnessing robust demand for sustainability. Manufacturers have adopted diverse strategies to align with these demands, leading to varying recommended practices across different countries. To thrive in today's competitive environment, industries, regardless of their scale, must demonstrate innovation despite their limited resources. This challenge is particularly pronounced for Small and Medium-sized Enterprises (SMEs) that face resource constraints in driving innovation, enhancing their products or processes, and achieving environmentally responsible outcomes. The significance of SMEs cannot be underestimated, as their sheer numbers necessitate an understanding of their ecological footprint to chart a course towards global sustainability. To formulate effective guidelines for reducing greenhouse gas (GHG) emissions, it is crucial to comprehensively understand the environmental impacts associated with existing manufacturing activities. Over the past two decades, environmental pressure has escalated across nations, resulting in the formulation of new international protocols. Consequently, the public sector and major corporate entities are increasingly integrating public and ecological responsibility into their structures, strategies, and governance frameworks to ensure sustainability (Giovannoni and Giacomo 2013; Knot, Van den Ende, and Vergragt 2001). Concurrently, prominent global institutions, governmental policymakers, and academic researchers have intensified their emphasis on environmental and social sustainability to maintain ecological equilibrium. Recognising that isolated efforts are inadequate for achieving sustainable development, a collaborative approach is imperative across various dimensions, including social, economic, ecological, and monetary aspects. Recent studies underscore the multifaceted nature of sustainability, highlighting that any viable sustainable state

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arises from interactions among organisations, individuals, societies, and states (Gray 2010; Jagtap et al. 2023). In an era marked by finite resources and persistent environmental impacts, the imperative for a more sustainable lifestyle becomes evident (Jitender and Sarkar 2017; Ljungberg 2007). The concept of sustainability gained prominence in the late 1990s, gradually shifting its focus from ecological concerns to encompassing broader sustainability objectives. Coined by the Brundtland Commission in 1987, the term 'sustainability' has become commonplace among policymakers, researchers, and non-governmental organisations (NGOs) (Jitender and Sarkar 2017; Robert and Patten 1995; Virtanen, Siragusa, and Guttorm 2020). Sustainability is now incorporated into every assignment of corporate statements (Jitender and Sarkar 2017). Thus, sustainable evolution is an evolution that encounters the requirements of the existing time without negotiating the facility of upcoming future generation to fulfil their personal needs (Cassen 1987; Jitender and Sarkar 2017; Sankar et al. 2024). The concept of sustainable development is intricately linked to various critical concerns, including equity, poverty alleviation, population control, safety, and environmental preservation. Broadly speaking, sustainable development is categorised into three dimensions: economic (profit), social (people), and environmental (the planet). When pursuing sustainable development, adopting a holistic perspective on product growth involves considering the entire lifecycle of the object and its influence across its stages, encompassing strategy, production, usage, and the final phase. This comprehensive approach is encapsulated by the concept of Triple Bottom Line (TBL) (Reinout, Huppes, and Guinée 2010).

The TBL is a transformative concept that promotes environmentally conscious practices by integrating social and economic considerations (Jayasinghe, Liyanage, and Baillie 2021; Lee and Mao 2015). It establishes a structured framework for evaluating an organisation's overall performance and its contributions through environmental, social, and economic dimensions (Defalque et al. 2021). Often referred to as a practical model for sustainability, the TBL framework places consistent and balanced emphasis on the social, economic, and environmental values that institutions bring forth (Okumura, Tasaki, and Moriguchi 2014; Ongwandee et al. 2020). Consequently, rigorous evaluation is essential for each stage of a product's lifecycle to gauge the sustainability of its manufacturing phases. This evaluation can be conducted either in a cradle-to-grave, cradle-to-gate, or gate-to-gate manner as part of the Life Cycle Assessment (LCA) of a product. Throughout this assessment, experts relied on tools and methodologies to ensure accuracy. It's vital to note that even minor adjustments or errors can yield significant consequences, such as the impact of raw materials on electricity consumption during the manufacturing cycle, the leftover materials post-production, and the ultimate phase of a product's life cycle (Clark et al. 2009).

Life Cycle Assessment (LCA) framework: The LCA framework, as depicted in Figure 1, adheres to the guidelines outlined in ISO 14,040 (Reinout, Huppes, and Guinée 2010). It commences with the 'goal and scope definition' phase, where practical measurement units and physical boundaries of the assessment are established (Wencke, Reisch, and Thøgersen 2020). The foundation of comparison for different products or services, known as the 'functional unit', is crucially defined for analysis. Subsequently, during the 'inventory analysis' stage, the 'inputs and outputs' of resources and energy across the entire lifecycle of a manufactured item were identified. This includes the utilisation of raw materials and release of substances into the environment. By utilising these data, a comprehensive model of the resource inputs and outputs for the system can be formulated. In the phase of 'impact assessment', the consequences stemming from the utilisation of resources and the emissions generated are aggregated and quantified in terms of environmental impacts for the product or service. During the 'interpretation' phase, the outcomes are explained in more detail. Furthermore, this phase entails a scientific evaluation of the necessity and opportunities to mitigate the environmental impacts of products or services (Damtoft et al. 2008).

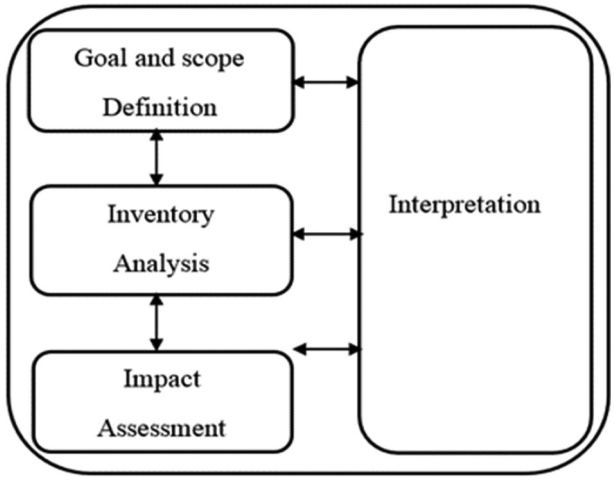

Figure 1. LCA as per ISO 14,040 (Reinout, Huppes, and Guinée 2010).

The process of assessing the environmental impacts of a product, process, or service throughout its entire life cycle is known as life cycle assessment (LCA). This encompasses the procurement of raw materials, manufacturing, consumption, and recycling or disposal.

Goal and Scope Definition: In this phase, the assessment's objectives, the boundaries of the system under study, and the functional unit – used to compare different processes or products – are defined (Cherubini et al. 2015).

Life Cycle Inventory (LCI): During this phase, data on all inputs (materials, energy, etc.) and outputs (waste, emissions, etc.) associated with every stage of the product's life cycle are collected (Brondani et al. 2020).

Life Cycle Impact Assessment (LCIA): Here, potential environmental impacts such as greenhouse gas emissions, resource depletion, or water pollution are calculated based on the inventory data. Various impact categories are considered using environmental indicators.

Interpretation: The findings from the impact assessment are analysed and evaluated in relation to the established scope and objectives. This process may include sensitivity analysis, uncertainty evaluation, and comparison with other scenarios or products.

Initially, LCA was predominantly applied within the manufacturing sector (Kaliyan, Sengupta, and Poovazhagan 2018). However, over time, researchers have expanded its use to various other domains, including supply chain management (Lamba and Prakash Singh 2018), food and beverage industries (Sharma et al. 2018), civil construction (Ding 2008), and product design (Clark et al. 2009). LCA is mainly implemented in manufacturing to reduce radiation or carbon emissions, covering the entire lifecycle of a manufactured product. LCA aims to comprehensively identify all inputs involved in the manufacturing process, starting from raw material acquisition to product end-of-life. It considers not only virgin material flows but also fuel and electricity consumption during production (Reinout, Huppes, and Guinée 2010). This approach encompasses all production stages, from resource extraction and treatment to distribution, usage, and post-consumer handling like recycling and disposal. Throughout each stage, material and energy flows are meticulously tracked to inform decisions at corporate and strategic levels (Vivanco et al. 2022). Despite its limitations, LCA plays a crucial role in informed decision-making in policymaking and business contexts (Bäckstrand 2003; Mccool and Stankey 2004).

Furthermore, LCA has been applied to assess specific domains such as urban agriculture (Ang, Ng, and Pham 2013), optimal municipal solid waste management systems (Feo De and Malvano 2009), gas emissions from metallurgical processes and salt removal from wastewater (Bogacka et al. 2022), and alternatives to plastic bags (Gómez and Serna Escobar 2022).

1.1. Applications of LCA

LCA has also been conducted to detect key environmental hotspots and study the ecological effects of a biochar-soil system (Muñoz et al. 2017). Energy analysis was conducted in the UK steel sector in 1994, showing that process enhancements and improved reprocessing within the life cycle can reduce energy intake (Michaelis, Jackson, and Clift 1998). According to Monteleone (2015), LCA plays an important role in improving household boilers in the UK, addressing particulate matter issues. Ingarao (2011) provided guidelines for evaluating technologies in sheet metal-forming industries, highlighting their savings, advantages, and disadvantages. Energy analysis was also conducted in 1994 in the U.K steel sector, and studies have shown that process enhancement and improved reprocessing within the life cycle will reduce the energy intake (Michaelis, Jackson, and Clift 1998). Soares (2013) used LCA to assess healthcare waste systems at different stages using autoclave, microwave, and lime techniques. LCA techniques have also been used to evaluate the environmental performance and energy efficiency of buildings (Ingrao et al. 2018), integrating with life cycle cost analysis to assess impacts on both the environment and building economics (Kun et al. 2021). Similarly, to enhance the ecological effects of farming activities like milk and rice production in the European Union, the Dutch government introduced numerous ecological strategies (Liu and Savenije 2008; Thomassen et al. 2008). In LCA, analysts identify gate-to-gate processes with high consumption of energy, water, and raw materials compared to others, seeking alternatives to reduce resource consumption or CO_2 emissions. However, reducing consumption or emissions may be limited in processes where levels are significantly high compared to others. In recent years, LCA has become a universally accepted tool, widely used in the farming sector to calculate ecological effects and identify hotspots (Ziegler and Valentinsson 2008). For instance, comparing organic and conventional farming systems helps identify significant areas for reducing carbon emissions and increasing productivity (Boone et al. 2019). A case study on milk production assessed hotspots of organic versus conventional processes using off-farm cradle-to-grave LCA to evaluate environmental impacts (Thomassen et al. 2008).

The primary objective of this research is to mitigate CO_2 equivalent emissions through LCA implementation. This study focuses on micro, small, and medium-sized industries, which contribute approximately 41.2% to global GDP. Specifically, the study examines gate-to-gate processes within the manufacturing realm of these industries.

The investigation centres on three companies producing identical components and products with similar designs. However, it's important to acknowledge the limitations of the LCA approach. While it quantifies CO_2 equivalent emissions effectively, it doesn't inherently reveal which manufacturing processes have the greatest potential to reduce these emissions substantially. This is because assessing CO_2 equivalent emissions alone doesn't show whether processes with higher initial emissions can achieve greater reductions compared to processes with lower initial emissions.

2. Aim and methodology

Unlike many previous studies that have primarily focused on identifying energy consumption and emissions, this current research endeavours to take a more comprehensive approach. The aim is to employ LCA to uncover environmental hotspots, enabling business enterprises to pinpoint key areas for potential improvements. This includes immediate reductions in excessive energy consumption and CO2 equivalent emissions, while also optimising the allocation of resources. The practical outcomes of this research are significant as they encompass a reduced carbon footprint for products, diminished reliance on virgin resources and energy consumption, minimised resource wastage, and enhanced fiscal gains. In this study, the focus is on three manufacturers within the 'bathroom fittings and sanitary' sector, all producing identical products featuring similar components such as water taps, wall mixers, nozzle sprays, and jets. The specific focus centres on the 'wall mixer' component, and this analysis entails a thorough examination of raw material consumption, energy utilisation, and greenhouse gas emissions throughout each stage of its lifecycle.

Procedure: The procedure unfolds with the utilisation of Equation 1, where the average CO_2 equivalent values for each gate-to-gate process undertaken by the three distinct companies are calculated.

$$X_{jAvg.\cdot} = \frac{\left[X_j - \left\{\frac{\sum_{j=1}^{j=X} X_j - X_j}{n-1}\right\}\right]}{X_j}$$

Subsequently, analogous emissions from the subsequent production stages of the same component produced individually by these three companies were compared (Section 4-5). This comparison yields normalising values, which in turn aid in deriving the average CO_2 equivalent emissions. Variations in CO_2 equivalent releases and power usage are then determined for each manufacturing phase in comparison to the minimum and average values for the same process across all manufacturing industries. This process establishes a provisional benchmark and designates the points with significant deviations as potential hotspots. Hotspots are categorised systematically for each manufacturing process, both within individual companies and collectively. An actionable framework emerges for firms with limited resources (time, personnel, and finances) to address and reduce CO_2 equivalent emissions. They are advised to prioritise addressing the first identified hotspot, followed by subsequent ones. This strategic progression offers a methodical approach for firms to efficiently manage their efforts towards emissions reduction.

3. Life cycle impact assessment (LCIA) (collection and examination of data)

Information from three different bath fitting firms, labelled as 'A', 'B', and 'C', has been organised systematically. All three firms fall under the category of Micro, Small & Medium Enterprises (MSME). Initially, official permission was obtained from these companies to gather data for this research, focusing on the components manufactured by all three firms. One such component is the 'Wall Tap Mixer 33,420', illustrated in Figure 2, primarily used for mixing warm and cold water. A comprehensive data collection process was conducted involving these three MSMEs in the bath fitting industry (firms 'A', 'B', and 'C'), with a specific focus on the standard product, the 'Wall Tap Mixer 33,420'. Official approval was obtained from these businesses to commence the data collection process, granting direct access to their operations for recording purposes. The 'Wall Tap Mixer 33,420' serves as a representative element in this research. Thorough data collection methodologies were employed, utilising various tools and equipment. Events during the manufacturing process were meticulously recorded using stopwatches, including grinding, buffing, electroplating, as well as stages such as melting raw materials in a blast furnace, pouring of materials, machining, and testing. Cameras were also used to visually record the various manufacturing stages.

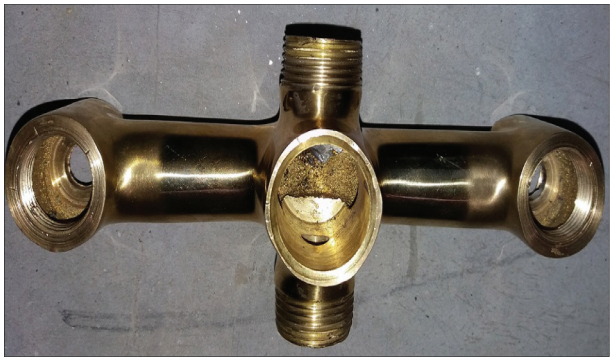

Figure 2. Wall tap mixer 33,420 (similar design manufactured by all the three companies).

The allocation of raw materials, component weights at various stages (post-casting, machining, grinding, and electroplating), and energy usage for multiple processes were recorded in great detail. Energy consumption data were calculated based on machine power ratings (Watt) and operation times.

In this study, major focus is on the Life Cycle Impact Assessment (LCIA), specifically concentrating on power usage for several reasons, notably due to resource scarcity and the significant environmental impact of energy use in manufacturing industries. Understanding a product's usage, transportation, end-of-life disposal, and other life cycle stages is essential for a thorough LCIA. However, this comprehensive method requires significant investments of time, money, and reliable data sources, which may not always be readily available. Constraints on time, money, and data availability often limit the scope of an LCIA. Given that energy consumption has a significant influence on greenhouse gas emissions, prioritising it as a critical environmental indicator in this study makes sense. Electricity usage in India, where coal-fired power plants contribute significantly to electricity production, directly contributes to carbon emissions, a serious environmental concern. Evaluating electricity usage, a crucial component of manufacturing processes, provides valuable insights into environmental sustainability. Compared to comprehensive data on other environmental impacts, detailed statistics on energy use are often more accessible and reliable. Focusing the LCIA framework on electricity usage may be greatly influenced by this accessibility factor. Additionally, aligning the research with broader environmental objectives, the study may specifically concentrate on energy efficiency or reducing carbon footprint. By focusing solely on electricity usage, the study can offer targeted recommendations and actions related to energy efficiency measures in manufacturing, thus supporting overall sustainability objectives. The LCIA methodology selected also helps focus attention on specific impact categories. Some LCIA frameworks and tools emphasise energy-related effects due to their importance to the environment and regulatory concerns. Therefore, prioritising electricity usage aligns with broader environmental goals and methodological considerations.

Although the research team intended to use a FlukeTM energy metre for accuracy, difficulties arose because some of the machines had hidden electrical connections. Due to the temporary interruption of the production process, the research team estimated energy consumption by combining machine power ratings and operation durations. No details were overlooked during the data collection process, including careful observation of each manufacturing step, which involved monitoring water, sand, and material usage. Following this method of data collection, a summary of the information gathered from the three bath fitting companies, 'A', 'B', and 'C', is shown in Table 1. The motor specifications of each machine provided power ratings, which were used to calculate power

Table 1. Power consumption and CO_2 equiv. For manufacturing of component of 'A', 'B', and 'C' bath fitting companies.

Process	Steps	Power ratings (kW)			Duration (min.)			Power consum. (kWh)			CO_2 equivalent (kg)		
		A	B	C	A	B	C	A	B	C	A	B	C
Core making	Simple sand core	1	1	1	8	7	10	0.13	0.12	0.17	0.13	0.11	0.16
	Resin sand core	3.03	2.1	3.04	1	1	1	0.05	0.03	0.05	0.05	0.03	0.05
Total		4.03	3.1	4.04	9	8	11	0.18	0.15	0.22	0.18	0.15	0.21
Casting	Melting of raw material	40	285.17	40	1	1	1	0.67	4.75	0.67	0.65	13.93	0.65
	Pouring of material	60		60	1		1	1		1	0.98		0.98
Decoring	Fettling machine	3.73	0	2.98	60	0	60	3.73	0	2.98	3.65	0	2.92
Total		103.73	285.17	102.98	62	1	62	5.4	4.75	4.65	5.29	13.93	4.56
Rough grinding	Belt grinding	3.73	1.5	3.73	1	2	1	0.06	0.05	0.06	0.06	0.05	0.06
Machining	Lathe	3.73	2.24	3.73	6	5	6	0.37	0.19	0.37	0.37	0.18	0.37
	Capstan	5.96	5.97	5.97	2	1	1	0.2	0.09	0.1	0.19	0.1	0.1
Testing	Leakage testing	3.73	2.24	3.8	2	2	1	0.12	0.07	0.06	0.12	0.07	0.06
Grinding	Flat belt grinder	3.73	2.24	3.8	10	8	10	0.62	0.3	0.62	0.61	0.6	0.61
Polishing	Buff grinder	2.24	2.24	3	5	5	4	0.19	0.19	0.2	0.18	0.18	0.19
Total		23.12	16.41	2.98	26	23	4	1.57	0.88	0.2	1.53	1.18	0.19
Electroplating	Sk-40 + water	1	2	2	0.08	0.08	0.08	0	0	0	0	0	0
	NiS + Ni-Cl + boric acid + Brighter	1.49	4	4	20	20	20	0.5	1.33	1.33	0.49	1.31	1.31
	EC-94 + water	1	1	1	0.08	0.08	0.08	0	0	0	0	0	0
	cleaning	0	1	0.5	0	0.08	0.08	0	0	0	0	0	0
Total		3.49	8	7.5	20	20.08	20.08	0.5	1	1.33	0.48	1.31	1.31
Packaging	L D Bags	0	0	0	0	0	0	0	0	0	0	0	0
	Polythene	0	0	0	0	0	0	0	0	0	0	0	0
Total			0	0		0	0	0	0	0	0	0	0
Total		109.36	312.67	108.38							7.09	16.26	7.67

consumption by multiplying the motor rating by the length of each operation. The average CO_2 emissions produced during one kilowatt-hour (kWh) of electrical energy were used to calculate CO_2 emissions. According to Mittal & Sharma (2014), this translates to roughly 0.98 kg of CO_2 per kWh in the Indian context.

Table 1 presents a comprehensive overview of electricity consumption data across various manufacturing phases for companies producing the same product. Interestingly, despite all three industries adhering rigorously to an identical manufacturing process for the '33240 Wall Mixer' component, there emerges a discernible process-level differentiation. This discrepancy manifests in the varying amounts of electricity or power used by each company. Consequently, the assumption that identical manufacturing processes yield identical CO_2 equivalents or carbon emissions is incorrect. In this study, the primary research focus is on identifying a targeted approach to gauge the efficiency of each industry's manufacturing process relative to the other two. Ideally, all three companies should be capable of achieving the minimum CO_2 equivalent value for every phase of the product's lifecycle. However, this goal remains unattained due to inherent challenges and the resource-intensive nature of the endeavour. Consequently, the concept of average difference in calculations is employed, wherein CO_2 emissions from one industry are evaluated relative to the average carbon emissions of other industries, excluding the industry under analysis (as outlined in Equation 1). Table 1 highlights the existence of process-level disparities. Although all three companies adopt the same manufacturing process for identical components, their electricity consumption varies significantly, resulting in distinct CO_2 equivalents. The calculations for energy consumption were based on operational durations and power ratings of machines in watts. During this study, the primary objective is to uncover the efficiency differentials between each industry's manufacturing processes compared to the other two. To elucidate the collected data more comprehensively, the data was visually represented through three distinctive figures, namely Figures 3, 4 , and 5. Each figure employs bar graphs to vividly illustrate the CO_2 emissions associated with every manufacturing process.

Figure 4 depicts the manufacturing process of company 'A'. Within this company, the fettling machine stands out as the process that consumes the maximum amount of energy and

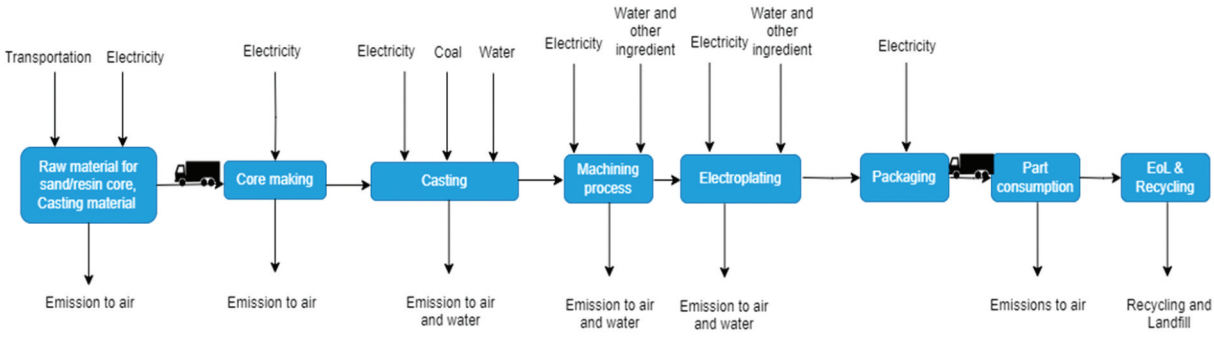

Figure 3. System boundary for cradle-to-grave analysis.

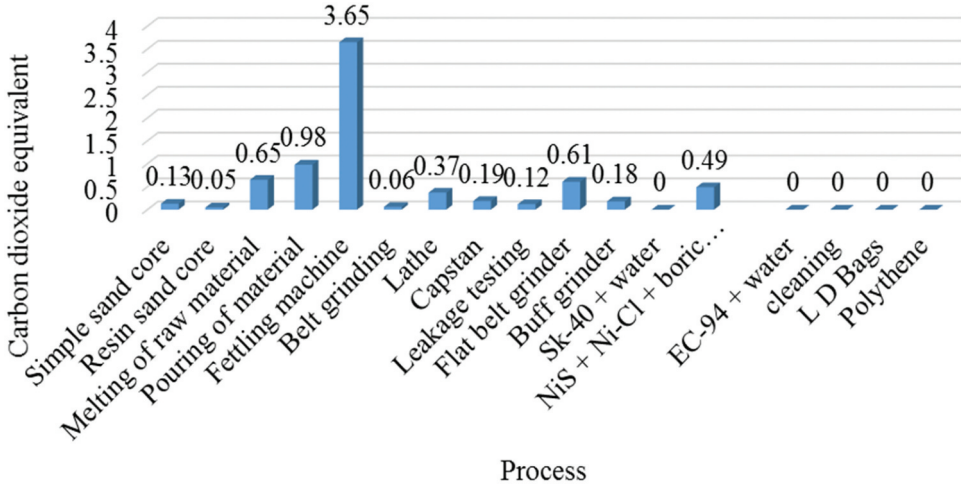

Figure 4. A CO_2 equivalent and energy consumption related to company A.

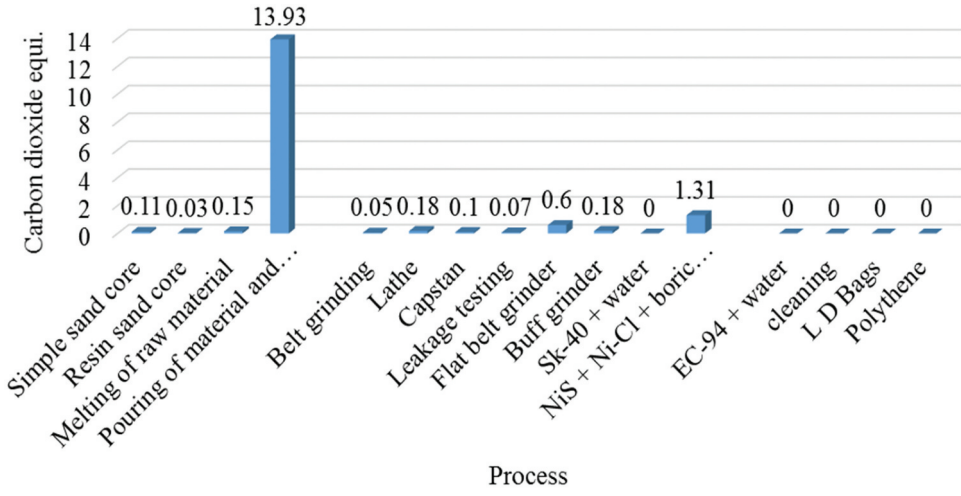

Figure 5. A CO_2 equivalent emission and energy consumption related to company B.

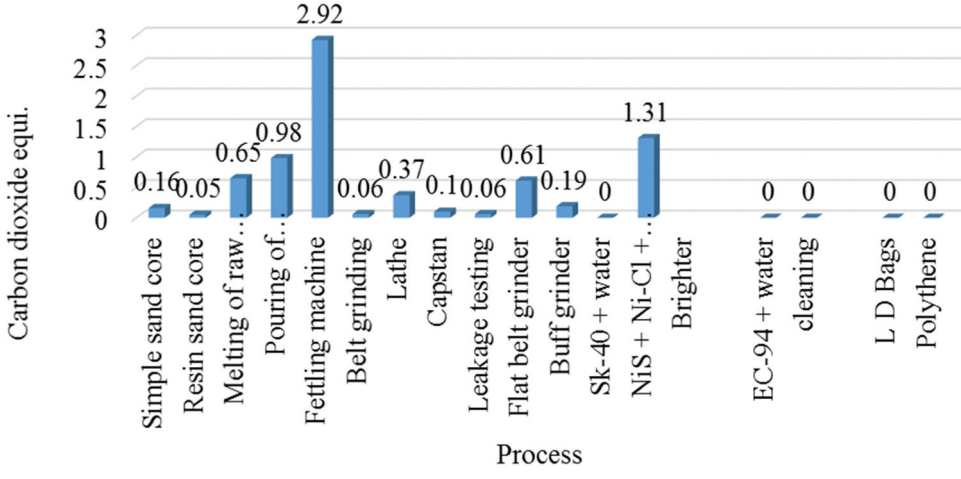

Figure 6. A CO_2 equivalent emission and energy consumption related to company C.

emits the highest amount of CO_2 equivalent (3.65 kg), particularly after the pouring and melting of raw materials, which is the initial stage with the highest energy consumption. Additionally, the pouring material machine, the process of melting raw materials, and the flat belt grinder machine also contribute significantly to energy consumption and CO_2 emissions, emitting 0.98 kg, 0.65 kg, and 0.61 kg of CO_2 equivalent, respectively.

Figure 5 illustrates the manufacturing process analysis of company 'B'. In this company, the pouring and melting of materials (casting process) consumes the maximum quantity of power and also emits the highest quantity of CO_2 (13.93 kg). This is followed by the nickel-chrome plating process and cleaning stages, which also contribute significantly to energy consumption and CO_2 emissions, emitting 1.31 kg and 0.60 kg of CO_2, respectively, during the manufacturing process.

Similarly, Figure 6 shows the manufacturing process of company 'C'. In this company, the fettling machine consumes the highest amount of energy and emits the highest amount of CO_2 (2.92 kg). Subsequently, in the electroplating section, nickel plating consumes the highest energy and produces 1.31 kg of CO_2. Additionally, the melting and pouring of raw materials consume the third-highest amount of energy and emit 0.65 kg and 0.98 kg of CO_2, respectively. The flat-belt grinder machine also contributes significantly to energy consumption. From Table 1, it is observed that each company consumes a different amount of electricity during the manufacturing of the same product. In fact, there is a process-level difference; although all the firms follow the same process to manufacture the same component, they use different amounts of electricity. Consequently, CO_2 equivalent emissions also vary accordingly.

4. Results and discussion

Table 1 demonstrates that the electricity consumption during the manufacturing of the same product varies across different companies. Indeed, there is a process-level difference; despite all three companies following the same manufacturing process for the same component, they use varying amounts of electricity. Consequently, the resulting CO_2 equivalent emissions also differ. The next objective is to determine how efficiently each company utilises its resources. Ideally, all companies should be able to achieve the minimum greenhouse gas (GHG) value for each stage; however, this may be challenging and resource-intensive. Therefore, the concept of average difference is utilised in calculations. The emissions generated by each industry are measured relative to the average of others, excluding the company being analysed (as per Equation 1).

The accuracy of predictions and benchmarks relies heavily on the quality and accuracy of the data. Additionally, when dealing with an unknown company, collaboration and data sharing with that company can enhance the accuracy of predictions and the effectiveness of benchmarking techniques.

$$X_{jAvg.} = \frac{\left[X_j - \left\{\frac{\sum_{j=1}^{j=X} X_j - X_j}{n-1}\right\}\right]}{X_j}$$

Where $X_{jAvg.}$, X_j, and n are 'average value of CO_2 equivalent emission of different process', 'value of carbon emission of a process' and 'number of processes', respectively.

Using Equation 1, the score for each phase of the life cycle for every small-scale manufacturing company was quantified. On this basis, a score was generated, and each process was arranged as shown in Table 2 and Figure 5. Thus, the assessment aims to evaluate how each company performs relative to others during the phase of the life cycle or stage of manufacturing of a component. Here, a 'Wall mixer 32,850' is considered for this study.

Table 2. GHGs emission for manufacturing of component by 'A', 'B', and 'C' bath fitting companies.

CO_2 equivalent (kg) for each process			
Process	A	B	C
Core making	00.00	−30.00	21.43
Casting	−74.76	64.64	−110.74
Machining	55.22	27.11	−6.13
Electroplating	−172.91	91.98	91.98

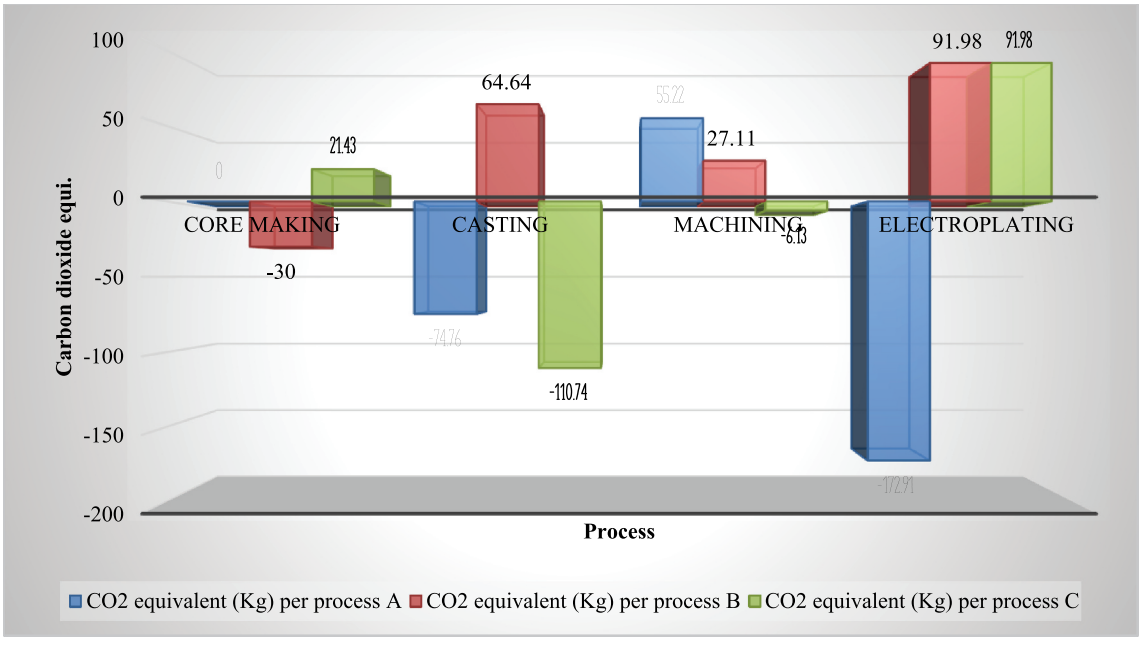

Figure 7. GHGs for manufacturing of component by "A", "B", and "C" bath fitting.

Table 3. Manufacturing processes according to highest probability to reduce CO_2 equivalent (hotspot) in descending order.

Company	Process	Hotspots
B	Electroplating	91.98
C	Electroplating	91.98
B	Casting	64.64
A	Machining	55.22
C	Machining	27.11
C	Core making	21.42
A	Core making	0
C	Machining	−6.13
B	Core making	−30.00
A	Casting	−74.76
C	Casting	−110.74
A	Electroplating	−172.91

For example, a company 'C' received 21.43 score in core making by using Equation 1 as: $X_j = 0.21$, $\sum_{j=1}^{n} X_j = 0.54$, $n = 3$ and $X_{jAvg.} = 21.43$ Figure 7 shows a representation of the data calculated using Equation 1, and the collection is presented in Table 2.

In Figure 7, all companies are represented using three different colours: orange, blue, and grey. From the data presented, it is evident that in the case of the electroplating process, company 'A' has the lowest carbon emissions compared to the other two companies. Similarly, in the case of the casting process, only company 'B' exhibits high CO_2 emissions compared to the other two companies, as illustrated in Figure 7.

Table 3 presents the arrangement of CO_2 equivalent emissions in ascending order. After calculating the CO_2 emissions using Equation 1, phase-wise information is obtained to identify opportunities for reducing CO_2 emissions from each company. The table highlights a hotspot for each process with respect to its manufacturing company, as demonstrated in Table 3. The data from Table 3 are visually presented in Figure 8.

After analysing each process in the component or product lifecycle of the three companies, it was discovered that in the core making process, company 'C' consumes a large amount of energy for core production (using sand core and resin coating) and emits a substantial volume of GHGs. In contrast, company 'B' exhibits the lowest energy consumption for this process. Replacing company 'C''s core making process with that of company 'B' could lead to significant reductions in CO_2 equivalent emissions. Additionally, transitioning from non-renewable electricity sources to renewable ones is recommended, despite the higher installation costs. These investments are expected to be recouped within one and a half years. Utilising pre-coated high-grade resin-coated sand with a catalyst and phenol-formaldehyde (PF) resin offers several advantages, including being free-flowing and smooth, providing strong cores and moulds, and exhibiting high resistance to peeling and moisture, which contributes to enhanced sustainability.

In the second process, specifically in the casting process, company 'B' consumes the highest amount of energy and emits a significant volume of GHGs compared to the other two companies in the manufacturing process. Instead of using a coal furnace like company 'B', switching to the furnace used by company 'A' could lead to cost savings and boost the company's economy. The fuel cost for coal used by company 'B' is 13.50 Rupees (0.21 USD), whereas the heating source used by the other company is electricity, costing 8.85 Rupees (0.14 USD) for melting the same amount of metal. Although the initial installation cost of the furnace is high, around $3, 675.00 USD, this investment can be recovered in approximately 4 to 4.5 years. This study also revealed that some companies use scrap material while others use pure virgin material for product manufacturing. Melting scrap material can lead to challenges when contaminants like lead and sulphur, already present in the scrap, affect the desired properties

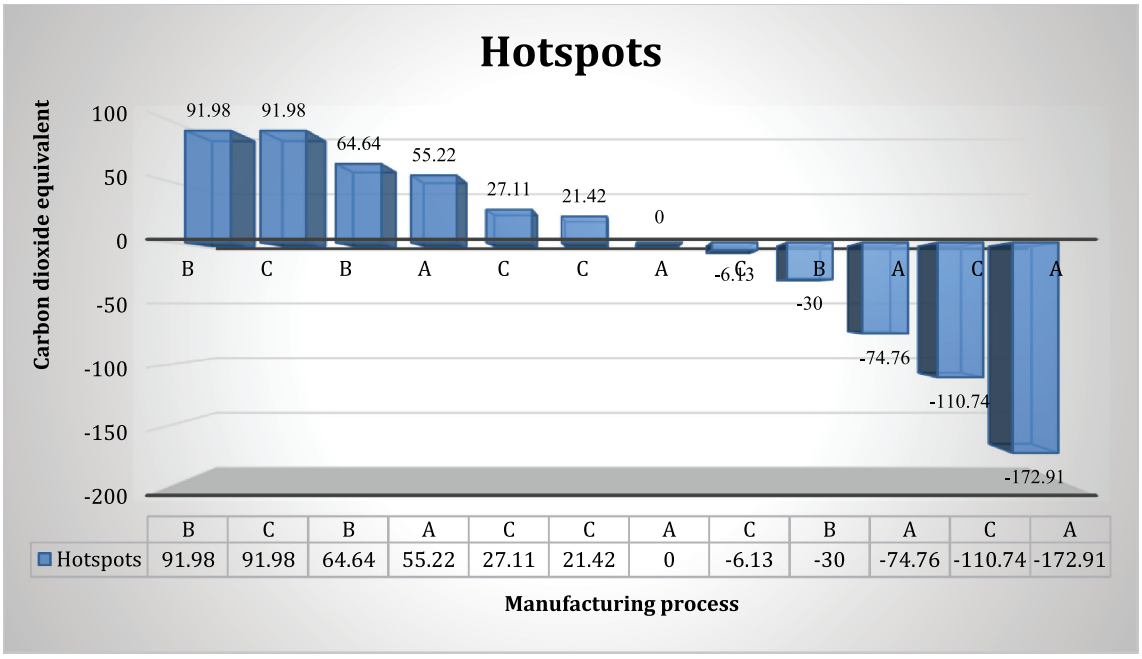

Figure 8. The arrangement of a manufacturing process according to highest probability to reduce CO_2 equivalent (hotspot).

of the obtained material. This process results in electricity wastage, GHG emissions, and economic losses.

In the third process, specifically the machining process, companies 'A' and 'C' consume the highest amount of energy and emit a large volume of GHGs. In contrast, company 'B' consumes the least amount of energy and emits the lowest amount of GHGs for the same process. For instance, in the testing section, both 'A' and 'C' use 3.73 kW of energy for defect detection, while 'B' uses only 2.24 kW. Replacing the 3.73 kW motor with a 2.24 kW one could result in significant energy savings and reduced emissions. Additionally, considering a renewable energy source instead of a non-renewable one for the motor input can further contribute to sustainability.

During electroplating, company 'B' consumes a considerable amount of energy, wastes water, and emits GHGs, particularly in the nickel-plating section, compared to the other two companies. This is attributed to their lack of awareness of the motor's power rating required for filtration and agitation of the nickel solution in the plating tank. Company 'B' also wastes three times more water compared to 'A' and 'C'. The assembly and packaging sections use approximately the same amount of manual power and energy. By applying Equation 1, a sustainability score for each process of each company was calculated. Based on this score, processes were ranked and ordered, as shown in Table 2. This ranking helps identify processes with the highest carbon emissions (hotspots) for small- and medium-scale industries, as presented in Table 3. Research indicates that current induction furnaces can achieve electrical efficiency levels exceeding 97% (Gandhewar, Bansod, and Borade 2011).

5. Conclusion

Sustainability is a critical consideration for industrial designers, managers, policymakers, and environmentalists. Industrial designers and companies are actively seeking ways to reduce carbon emissions across each phase of a product's life cycle. However, achieving reductions in carbon emissions requires significant resources such as financial investment, human resources, and time. Throughout a product's life cycle, there are various approaches to mitigate its environmental impact. However, not all methods are equally effective in reducing carbon emissions. Some methods may require substantial natural resource consumption and effort, while others may be less resource-intensive. Comparing the processes followed by different companies manufacturing the same product can help determine which approaches are more or less resource-intensive and challenging to implement. In this study, the focus was on a tap water component manufactured by three different Micro, Small & Medium Enterprises (MSMEs). This study is unique in its exploration of the MSME sector and involves conducting a life-cycle assessment to collect data across each stage of the product's life cycle. Quantifying CO_2 emissions for each life cycle phase allows us to identify areas where achieving emissions reductions is challenging. With Equation 1, specific manufacturing stages of the same product produced by different companies with varying manufacturing processes can be compared. This comparison allows us to understand how much carbon emissions can be reduced by optimising specific manufacturing processes for each company. This study involved analysing the life-cycle energy expenditure for each manufacturing stage of the component produced by each company Determined the average and minimum energy requirements for manufacturing this component, providing insights into each industry's performance across different manufacturing phases and opportunities for improvement in emission hotspots. This approach helps identify areas where interventions can lead to significant reductions in environmental impact.

This study's potential for benchmarking approaches in life cycle assessments (LCAs) represents a significant paradigm shift in sustainability practices, which is one of its major contributions. Assuming that if one company can practically manufacture the same component with a less energy-intensive process in one manufacturing stage, other companies should also be able to achieve similar efficiencies. A key contribution of this study is its capacity for benchmarking techniques in LCA, indicating a potential shift in sustainability practices. By demonstrating how businesses can implement less energy-intensive procedures to reduce emissions, information exchange and mutual learning among industry participants are facilitated. Leveraging the experiences of other businesses, this strategy supports organisations in transitioning to more environmentally friendly operations by addressing identified hotspots. Through learning from each other, the aim is to understand how companies manufacturing the same component using similar processes can generate fewer emissions, and then recommend adopting these practices to companies with hotspots. It is believed that adopting such practices will reduce emissions and hotspots, leading to sustainability outcomes with minimal effort. In conclusion, this research showcases how sustainability principles can be applied in real-world settings beyond laboratory environments. While acknowledging the need for more detailed mechanistic discussions and structured presentations of results, findings significantly contribute to ongoing discussions on sustainable engineering.

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Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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