Journal of Engineering Science and Technology Review 17 (2) (2024) 23 - 34

Research Article

JOURNAL OF
**Engineering Science
and Technology Review**

www.jestr.org

Comparative Analysis on Sustainability Parameters of Traditional Tool Manufacturing Processes Using Life Cycle Analysis Tools

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Received 14 June 2023; Accepted 19 April 2024

Abstract

Life Cycle Assessment (LCA) is a potent tool for evaluating the ecological consequences of various products and processes. However, with a plethora of LCA software tools (ST) available, selecting the most appropriate tool for a specific application can be quite challenging. This research paper aims to compare two popular LCA Tools, GaBi- a commercial software, and openLCA- an open-source, for a traditional tool manufacturing case study. The comparison considers factors such as user-friendliness, user support, modelling capability, cost, flexibility, comprehensiveness, and functionality. Impact categories representing human health, ecosystem, and resource consumption were chosen. The case study evaluated the Cradle-to-gate manufacturing of a turbine die made by traditional machining processes and used as a wax injection moulding die for investment casting. The study found that aluminum production and manufacturing were the highest contributors to total environmental impact due to electricity consumption and aluminium waste. The results indicate that each ST has unique features and capabilities suitable for specific applications. We calculated relative deviations as the ratio of maximum to minimum calculated impacts for comparison. Ozone depletion (22.57) and freshwater eutrophication (4.2) had the highest variation. Significant deviations in human toxicity (3.16) were observed using the ReCiPe, while climate change (1.58 and 1.66) was accurately assessed by both CML and ReCiPe. GaBi is found to be the most user-friendly and efficient tool for beginners, with great modelling capability and flexibility to handle complex systems, while openLCA is the most comprehensive tool for analyzing complex systems, grants functionality, and is freely available suggested for experienced users. This research paper provides a comprehensive evaluation of LCA ST for traditional tool manufacturing applications, which can help manufacturers make informed decisions in selecting the most suitable ST for their LCA needs.

Keywords: Sustainability assessment, Sustainable Manufacturing, Additive Manufacturing, Rapid tooling, Life Cycle Assessment, Investment Casting, GaBi, openLCA

1. Introduction

1.1 Background information on life cycle assessment (LCA)

Sustainable manufacturing is becoming increasingly important as the world becomes more environmentally conscious. One aspect of sustainable manufacturing is the assessment of the environmental impact (EI) of manufacturing processes, which can be done using Life Cycle Assessment (LCA) [1]. LCA is a crucial tool for evaluating the EI of products, processes, and services over their entire life cycle. LCA software tools (ST) quantify the EI of products, processes, or services. Product life begins with the extraction of raw materials to make a product and then analyzes different phases till disposal [2] as shown in Fig. 1. LCA aids organizations in recognizing opportunities to reduce the EI of their products, comply with regulatory requirements, and improve their sustainability performance. LCA ST is essential for conducting accurate LCA analyses [3-4].

1.2 Modules, features, and criteria for comparing LCA STs.

Performing Life Cycle Impact Assessment (LCIA) can be a complex and data-intensive task. To simplify this task, various options are available, including LCA Excel sheets and STs. However, while Excel sheets are limited and involve uncertainty, STs offer more intuitive and user-friendly results[5]. SimaPro, GaBi, openLCA, and Umberto LCA+ are the most commonly used STs for LCA. Each ST has a different speed, method, information, and flexibility. While initially designed for the packaging industry, these STs are now applicable across industries [6]. The STs support a variety of databases and impact assessment methodologies. GaBi supports the ecoinvent 3 database and CML2002/2007 or Eco indicator 95/99 methods, while SimaPro uses the ELCD ecoinvent database with Impact 2002, ReCiPe, and Eco indicator-99 method [7-8]. PE International develops in-house databases for GaBi, while other tools rely on external data sources. However, all software can access data from external sources like EcoInvent and the US LCI [9]. Germany, Netherlands, and the US dominate the field of LCI databases, LCIA methods, and LCA STs [10].

LCA ST typically comes with various modules that offer different features and capabilities. These modules may

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ISSN: 1791-2377
doi:10.25103/jestr.172.04

include inventory analysis, impact assessment, interpretation, social LCA, etc. Each module allows users to collect and input data, assess EI, interpret results, analyze social and economic impacts, assess water use and pollution, and calculate carbon footprints [11]. Choosing the right module(s) for a specific analysis can help users make more informed decisions based on the LCA results [12].

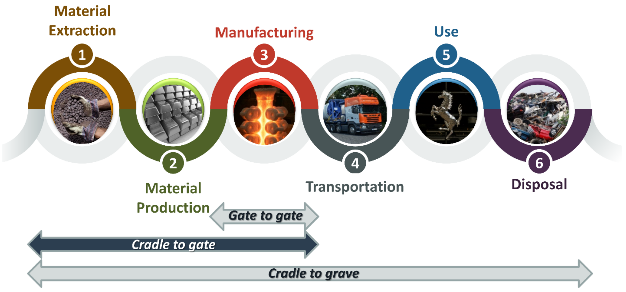


Fig. 1. Classification of product life cycle phases

LCA STs offer various modules, including inventory analysis, impact assessment, interpretation, social LCA, etc. Users can choose the appropriate module(s) to input data, assess EI, interpret results, and calculate carbon footprints for informed decision-making [12]. With the use of LCA STs, users could have benefits, such as reducing environmental footprints and increasing profits, enhancing industrial eco-design and development processes, allowing for comparison of different EI, supporting various sustainability strategies, and optimizing production [13-15]. However, selecting the most suitable LCA ST can be challenging due to the numerous options available. Therefore, it is essential to compare popular LCA ST based on their features, capabilities, and usability to make rational choices [16- 17]. The following criteria may be used for techno-economical comparative evaluation of LCA ST.

i. ***Performance***: It involves evaluating the accuracy and consistency of results generated by different software through comparison of the same LCA study;
ii. ***User-friendliness: it*** involves assessing ease of use, intuitiveness, and accessibility through user testing with LCA software users;
iii. ***Cost:*** It involves analyzing upfront costs, ongoing maintenance fees, and additional costs through conducting a cost-benefit analysis that considers organizational needs and budget; and
iv. ***Functionality:*** It involves assessing specific features and capabilities of each software by creating a feature matrix. However, the choice of comparison criteria and corresponding evaluation methods may depend on the specific goals [12], [18-19].

1.3 LCA STs and their significance: An Overview

With an increased number of tools available in the market for commercial and academic purposes, it becomes increasingly important to have some tool selection criteria to meet specific requirements. Some studies have been reported for software comparison aiding selection among available market options. Researchers compared SimaPro, CES EDUPACK, Sustainable Minds, Solidworks, and GaBi against different criteria like product definition creation, the flexibility of database updating, available LCIA methods, and presentations [20]. Researchers took a case to evaluate four STs SimaPro, GaBi, openLCA, and Umberto with the ILCD midpoint method, gate-to-gate (G2G), and cradle-to-gate (C2G) systems. They have concluded that G2G shows less variation of impact with software as compared to C2G; in C2G, the variation is due to characterization factors (CFs), which vary as per software [12].

Further, CF analysis shows that each software has different substance mapping systems. All four software, SimaPro, GaBi, openLCA, and Umberto, allow users to import data in office files. However, the i-report creation of GaBi is one step ahead, which gives the flexibility of customized graphs and charts according to changes in inventory [21].

The selection of impact assessment methodology depends on the midpoint and endpoint categories offered and relevant criteria for the study. For instance, non-renewable energy consumption is a midpoint indicator, and resource consumption is an endpoint category. Users are able to make modifications to the existing database in GaBi and SimaPro, and both software support the latest database definitions [22]. SimaPro uses a wide variety of databases and is more user-specific than GaBi. Additionally, SimaPro and openLCA allow for the comparison of two or more product systems at the same time or the same product system under different assumptions like allocation or target amount for instance. Users can make modifications to the existing database in both GaBi and SimaPro, and both software have updated database definitions. GaBi has an excellent user-friendly graphic interface for process modeling with a variety of CFs and offers the most dynamic facility to show the immediate impact result [12]. SimaPro is good at weighing impacts and observing comparative implications, making it a good option for full LCA studies due to its detailed LCI database and a range of LCIA methods [23]. Both GaBi and SimaPro have the latest databases with added flexibility to modify them. SimaPro also has an easy-to-use comparison function, which leads to design optimization with an effective presentation [20], [22].

By looking at other options, Solidworks creates product definition via CAD model only with very limited impact categories [20], and CES EDUPACK is a preferable choice for energy consumption and carbon footprint calculation [4]. Umberto LCA+ may pose a challenge for novices without prior experience in professional LCA to initiate. However, one can opt for Sustainable Minds, which has "what-if" scenario-based modeling [4]. openLCA allows users to easily compare two or more systems with a descent graphical representation of impacts [21]. Tab. 1 shows a summary of prevalent LCA software.

1.4 The rationale for this Research

This study examines turbine blade manufacturing as a representative example of traditional tool manufacturing processes. These blades, crucial for energy conversion, are prone to creep and fatigue stresses due to their complex geometry. Achieving precise shape and tolerances is essential. Turbine blade manufacturing involves two main technologies: CNC for tooling and investment casting for production. For 4000-6000 years [25], investment casting is the second-highest practiced casting technique known for its accuracy and precision but faces challenges such as lengthy production cycles, specialized tooling, skilled labor requirements, and waste generation. Careful examination of the investment casting (IC) process reveals that the primary bottleneck occurs during the tooling production stage, involving processes such as lathe work, drilling, CNC machining, VMC operations, and EDM techniques for manufacturing the IC die [26-28]. This prolonged lead time impedes the manufacturer's ability to meet market demands promptly, potentially jeopardizing their competitive advantage. The tooling production phase, particularly with traditional methods, can take 8 to 12 weeks. Historical records show similar challenges in crafting copper and bronze idols, taking approximately 3 to 4 months. Additionally, tool manufacturing entails significant resource consumption, leading to notable ecological impacts through energy and material usage. Therefore, this study conducts a Life Cycle Assessment (LCA) to evaluate the Environmental Impact (EI) of these processes [29].

Table 1. Summary of widely used LCA STs [4], [17], [21], [24]

Ref. No	Software	Developer	Suitability	Major Analysis Capability	Limitations
[4]	GaBi	Thinkstep, Germany	Life Cycle Assessment, Carbon and water footprint, Eco-design, Environmental Product Declaration, and Product Environmental Footprint, Resource & energy efficiency	• Impact assessment • Sustainability reporting • Carbon and water foot print • Product design • Environmental Product Declarations • Key Performance Indicators.	• Limited database
[17]	SimaPro	Pre-sustainability, Netherland	Impact assessment, sustainability reporting, carbon and water foot print, product design, generating Environmental Product Declarations, and determining Key Performance Indicators.	• Life Cycle Assessment • Carbon and water footprint • Product design • Environmental Product Declarations • Key Performance Indicators	• Complexity • Expensive
[21]	Umberto LCA+	ifu-Hamburg, Germany	Carbon Footprint, Life Cycle Assessment, MFCA, Life Cycle Costing, Environmental Product Declaration	• Carbon Foot print • Life Cycle Assessment • MFCA • Life Cycle Costing • Environmental Product Declaration	• Limited compatibility • Lack of advanced features:
[24]	OpenLCA	GreenDelta, Germany	Environmental Life Cycle Assessment, economic Life Cycle Costing, social Life Cycle Assessment, Carbon and Water Footprint, Design for Environment, Environmental Product Declaration, Environmental Product Footprint	• Environmental Life Cycle Assessment • Economic Life Cycle Costing • Social Life Cycle Assessment • Carbon and Water Footprint • Design for Environment • Environmental Product Declaration • Product Environmental Footprint	• Limited support • Database management:

This research paper aims to compare the effectiveness of LCA STs, in assessing the EI of traditional tool manufacturing processes. The study will examine the variation in results obtained from using these tools with identical input data and the same databases. The research will focus on the modules available in these STs, including inventory analysis, impact assessment, and interpretation with impact categories like water footprint, human health, and product carbon footprint. ST be evaluated for their user-friendliness, comprehensiveness, cost, and applicability to tool manufacturing processes. User-friendliness will be assessed based on ease of use and technical support availability, while comprehensiveness will be evaluated based on the level of detail provided by the software in LCA analysis. Suitability for tool manufacturing processes will be determined based on the software's ability to perform basic LCA analysis for such processes [30-31].

The objectives of the research are to:

i. Review the available LCA STs used for evaluating the EI and screen it for comparison.
ii. Through the investment casting (IC) process, identify the most resource-intensive stage and choose it for the LCA case study.
iii. Conduct the comparative analysis of the identified LCA STs in terms of their functionality, flexibility, user-friendliness, user support, modelling capabilities, comprehensiveness, and cost.
iv. Recommend the most suitable LCA ST for evaluating the EI based on the results and selection criteria.
v. Report the major contributing life cycle phases to EI and also identify the EI category and LCIA method showing the highest variance.
vi. Provide insights and recommendations for future research and development of LCA STs for evaluating the EI of traditional tool manufacturing processes.

Section 2 of the report centers on the selection of ST for comparison, experimental methodology, and the LCA of a chosen part, starting from defining the goal and scope and going up to the interpretation phase. Section 3, justifies the root cause behind the result discrepancies. Section 4 provides a detailed comparison of two selected LCA STs based on user experience and various software selection criteria. Sections 5 and 6 offer valuable insights and recommendations for researchers and practitioners who wish to conduct a comprehensive and effective EI assessment of manufacturing processes by comparing and evaluating the two selected LCA STs.

2. LCA Of Traditional Tool Manufacturing Process

2.1 LCA ST choice

This research aims to conduct an LCA study of traditional manufacturing of turbine tooling, which requires an LCIA method that can comprehensively evaluate the impact on human health, resources, and the ecosystem. This requires diverse data pertaining to tooling manufacturing. Due to the complex nature of product system development involving iterative processes, it is crucial to select the appropriate ST. Thus, the following steps have been used for selecting a suitable ST.

1. To select the most suitable ST, we followed a rigorous approach. Firstly, we identified SimaPro, GaBi, openLCA, and Umberto as STs that support a comprehensive LCI database for the turbine body. As industrial turbine LCIA data were not available in the literature, only SimaPro, GaBi, and openLCA were considered since they allow database modification. Compared to other options, Umberto lacks robust characteristic features and is not user-friendly, nor does it provide significant innovations.
2. Secondly, although SimaPro appears to have more robust characteristic features, it is overly complex to operate, and in literature, it is applied for construction engineering applications while Gabi offers a broad selection of databases that are well-suited for the manufacturing sector.
3. GaBi is a commercial ST supporting a larger database of materials and processes and advanced modeling capabilities, commonly used by companies for LCA studies. While openLCA is an open-source ST that is freely accessible, offering flexibility in adding user-specific data and models.
4. Both tools offer a user-friendly interface, rich LCI data as well as the ability to create customized models and scenarios. This led to the selection of GaBi 9.2.1.68 and openLCA 1.11 as the two STs to be compared using the ecoinvent 3.7.1 database.
5. By comparing these two STs, our study provides insights into the strengths and limitations of both commercial and open-source LCA STs, offering a comprehensive evaluation of LCA STs for sustainable traditional tool manufacturing [4], [17], [24], [32]. Fig. 2 shows the theme of current research.

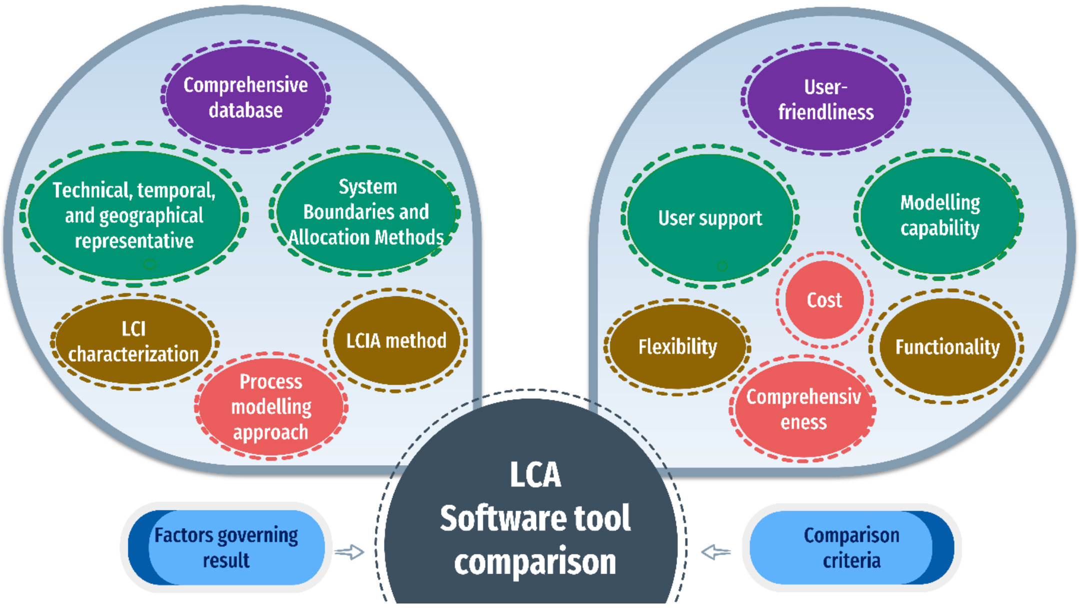


Fig. 2. The theme of current research

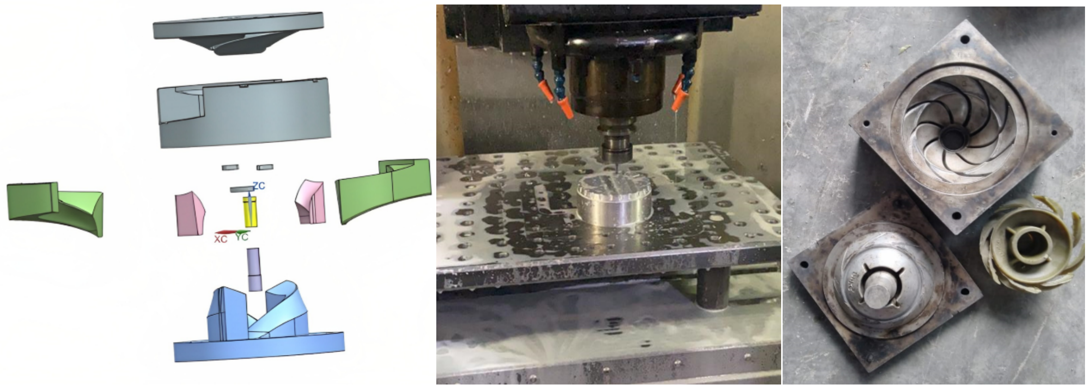
2.2 Case Study

The case of die manufacturing for Investment casting of the turbine blades has been selected for this research (Fig.3c). The manufacturing of Investment Casting (IC) tooling involves several stages, starting from the acquisition of raw materials to the final testing and quality control of the finished product. Cast aluminium ingots are preferred for die manufacturing, and the distance between the raw material supplier and tooling manufacturer is calculated to be 3.6 km [33-34].

The design of the turbine die is created using Unigraphics NX 1953, and a CAM program is created based on the design data. The raw material ingot is loaded onto a lathe, and facing and turning operations are performed to prepare the job for VMC. Multiple setups of VMC are required to manufacture the final die, and compressed air, coolant, and slide oil are used as lubricants during manufacturing on VMC.

After manufacturing on VMC, the die is transferred to a drilling machine where drilling and allied operations are performed to attach the two halves of the die with a nut and bolt. Finally, a spark erosion machine is used for finishing purposes, followed by manual cleaning and fitting, where nylon scrubbers, sandpapers, and cleaning agents are used to remove scratch marks and dirt.

The quality of the turbine die is then tested using a digital vernier height gauge, filler gauge, and go and no-go gauge. The entire manufacturing cycle takes approximately 56 days to manufacture the turbine die, and the software database provides the background data, while the shop floor is the source of foreground data consisting of design, machining, and quality control data. Fig. 3 shows an exploded view of the turbine die and its manufacturing.



(a) (b) (c)

Fig. 3. IC Turbine die manufacturing

2.3 LCA

The objective of the LCA methodology is to promote sustainability throughout all phases of industry in line with global standards, including ISO 14040 and ISO 14044[10]. As shown in Fig. 4 LCA involves four primary stages, starting with defining the study's objective and scope, followed by inventory analysis, and evaluating the environmental impact of the chosen component through EI assessment. The final step, which is the most crucial, involves interpreting the results, which requires a comprehensive understanding to determine the signs of improvement. LCA provides a comprehensive evaluation of the global impact of a product or material from its creation to disposal. Moreover, ISO 10993 offers guidelines for the utilization and disposal of end-of-life products [35].

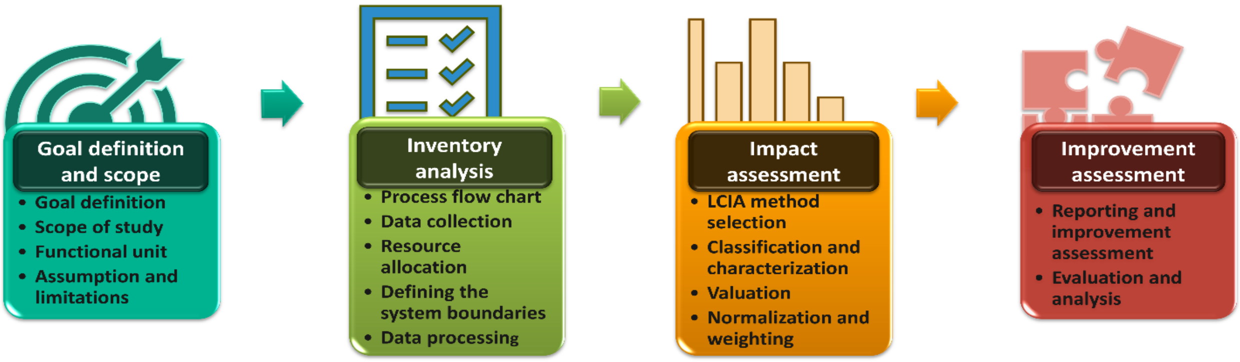


Fig. 4. LCA framework [35-36]

(1) Goal and scope definition

a) **System Boundaries:** Cradle-to-gate analysis

A comprehensive LCA involves analyzing the entire life cycle of a product, which starts from resource extraction and ends with disposal or recycling. Cradle-to-gate LCA evaluates the product life cycle from resource extraction to the manufacturing phase, while gate-to-gate LCA only focuses on the value-adding or manufacturing stage. In this study, we will only focus on the value-added processes during the cradle-to-gate production cycle, with importance given only to the inputs and outputs during the material production, design, and manufacturing stages. As such, we will carry out a partial LCA of the IC turbine die. Fig. 5 shows the selected boundary of the study.

b) **Functional unit:** To produce a single unit of IC turbine die by traditional tooling production.

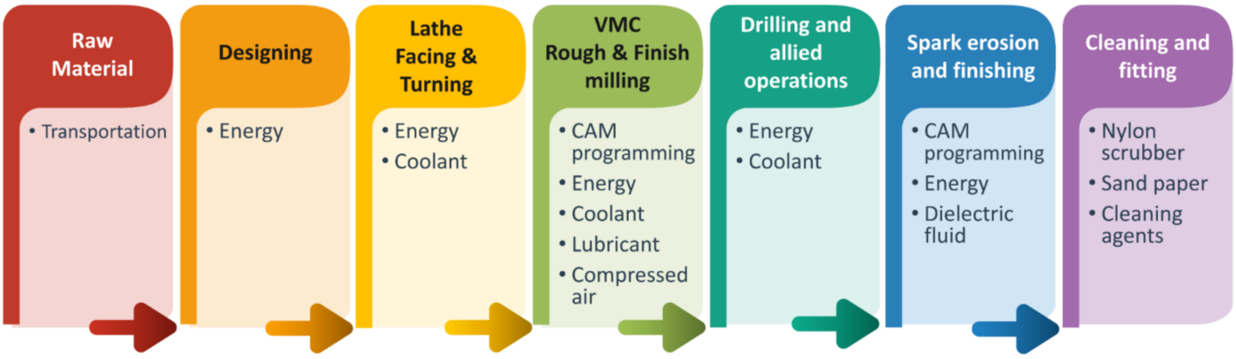


Fig. 5. Cradle-to-gate life span of turbine die manufacturing

(2) LCI

The IC die manufacturing phase involves several distinct operations, some of which require repetitive VMC milling cycles. These cycles consume a significant amount of time and energy, as well as materials, and generate waste. Tab. 2

provides the Life Cycle Inventory (LCI) data collection for the IC turbine die manufacturing process.

Table 2. LCI data

Sr No.	Manufacturing Stage	Weight (kg)	Time (hr)	Energy (kWh)
1	Raw Material	93	-	-
2	Designing	0	3	0.98
3	Facing and turning on a lathe	75	7	2.1
4	Rough milling	64	19	7.49
5	Finish milling	58.8	25	9.85
6	Drilling and allied operations	57.34	16	1.89
7	Spark erosion and finishing	57	6	5.5
8	Manual cleaning & Fitting	0	4	
	Total	**Material removed 36kg**	**57hr**	**22.84 kWh**

(3) Life Cycle Impact Analysis (LCIA)

Life Cycle Impact Analysis (LCIA) requires an understanding of material, energy, and fluid flows. Data on IC turbine die production was used to create an inventory model for impact assessment, covering the entire manufacturing process. Two LCA software programs, openLCA, and GaBi, were used to model the process. GaBi offers more visual enhancements, such as color-coding, compared to openLCA which only allows for process connections.

a) **LCIA method:** CML 2001, ReCiPe 2016 midpoint (H)

During the manufacturing of toolings, various harmful waste streams such as cyanide, mineral oils, phenols, and heavy metals are discharged into the surroundings. To evaluate the impact of these waste streams, we screened two LCIA methods that are globally applicable: CML 2001 and ReCiPe 2016 midpoint (H). These methods were chosen for their range of impact categories that are relevant to the current scenario.

CML

The University of Leiden, Netherlands developed the CML 2001. It includes a total of 1700 flows, which can be downloaded from the university's website. It is split up into baseline and non-baseline categories, with the former being the most commonly used. It provides CFs for both baseline and non-baseline impact categories such as GWP100, HTP, and ODP for baseline categories and GWP20, GWP50, GWP100, ODP10, and HTP100 for non-baseline categories. Additionally, the method offers other characterization methods like Eco-indicators and EPS. Normalization data is included for all interventions and impact categories, covering various spatial and temporal levels [37-38]. Among the 8-impact category group of CML baseline, climate change, and human toxicity are considered here.

ReCiPe

In 2016, the CML and Ecoindicator-99 methods were combined into a new method called ReCiPe 2016 that can calculate EI at both midpoint and endpoint categories. It covers impacts from metal and polymer processing and has 18 midpoint and 3 endpoint categories, namely human health, resources, and ecosystem [37],[39]. The conversion of LCI results into EI indicators takes place in the characterization phase through the multiplication of individual inventory data from the LCI with CFs. The impact indicators TAP, FEP, GWP, HTP, ODP, and ULOP are characterized based on the ReCiPe for 2016, while those for GWP and HTP are based on CML2001. To ensure comparability between different impact categories, the method includes normalization, which involves dividing the impact indicator by a reference value, as shown in equation (1). This is considered an important step in the process. After normalization and weighting of the variables, the method computes an integrated score expressed in "points" that reflects the EI per job. The unit of measurement for these "points" is mPt, and a higher number of "points" indicates a larger EI [40].

$$N_j = \frac{\sum_i Q_{ji} \times CF_{ji}}{NF_j} \qquad (1)$$

The above equation represents the calculation of the normalization result (Nj) for a given environmental indicator (j). It takes into account the sum of resources or emissions categorized under indicator j (Qji) and the related characterization factor (CF) of that resource or emission (CFji). Additionally, the equation incorporates a normalization factor (NFj) specific to indicator j. This equation is commonly used in LCA studies to compute the EI of a product or service.

b) **LCI results**

The LCIA results involve the classification of each substance or resource extraction added to the process into subgroups such as air, freshwater, seawater, agricultural soil, and industrial soil. The classification data for this section are based on the operational guide of ISO 14044 from the LCA handbook.

The effectiveness of LCIA results is determined by the proper choice of impact categories and the LCIA method. In this investigation, the ReCiPe 2016 LCIA method was selected for comparison, which includes eighteen midpoint impact categories as shown in Tab. 3. From these categories, we picked the six most significant impact categories by looking at the tool manufacturing problem for comparison with contemporary LCIA methods, representing ecosystem, human health, and resource impacts. Climate change was included as a critical impact category, given its destructive effects on the planet and its recognition as a global threat by the UN's 17 Sustainable Development Goals [41]. We also shortlisted ozone depletion, human toxicity, acidification, urban land occupation, and freshwater eutrophication as impact categories, with justifications provided in Tab. 4.

Table 3. Total impact categories: ReCiPe 2016

	Endpoints	Impact category	Unit
1	**Ecosystem impacts**	Freshwater ecotoxicity – fetpinf	kg 1,4-DCB-Eq
2		Marine ecotoxicity - metpinf	kg 1,4-DCB-Eq
3		Terrestrial acidification - TAP100	kg SO2-Eq
4		Agricultural land occupation – ALOP	m2a
5		Natural land transformation – NLTP	m2
6		Freshwater eutrophication – FEP	kg P-Eq

7		Climate change - GWP100	kg CO2-Eq
8		Terrestrial ecotoxicity - tetpinf	kg 1,4-DCB-Eq
9		Marine eutrophication – MEP	kg N-Eq
10	**Human health impacts**	Ionizing radiation - IRP_HE	kg U235-Eq
11		Particulate matter formation - PMFP	kg PM10-Eq
12		Human toxicity - htpinf	kg 1,4-DCB-Eq
13		Photochemical oxidant formation - POFP	kg NMVOC
14		Ozone depletion – odpinf	kg CFC-11-Eq
15	**Resource impacts**	Metal depletion – MDP	kg Fe-Eq
16		Urban land occupation - ULOP	m2a
17		Water depletion – WDP	m3
18		Fossil depletion - FDP	kg oil-Eq

Table 4. Chosen impact categories, their importance, and results

	Impact category	**Unit**	**Justification**	**GaBi (ReCiPe)**	**openLCA (ReCiPe)**	$R_{max/min}$
			Ecosystem impacts			
1	Terrestrial acidification - TAP100	kg SO2-Eq	Considers acidification potential due to Nox and SO2 emissions; ***acid rain***	0.233	0.162	1.43
2	Freshwater eutrophication – FEP	kg P-Eq	Accumulation of nutrients (P and S) aquatic system; algae and plant growth; **damage to water quality, ecosystem, and animals**	0.084	0.02	4.2
3	Climate change - GWP100	kg CO2-Eq	Global temp. change due to GHGs (greenhouse gas), difficult to handle due to broader scale; **Climatic abnormalities, temperature change, biodiversity decrease**	26.6	42.16	1.58
			Human Health			
4	Human toxicity - htpinf	kg 1,4-DCB-Eq	Toxicological effects on humans and chemicals in the human body system; ***cancer, respiratory diseases, and non-carcinogenic effects***	5	15.8	3.16
5	Ozone depletion – odpinf	kg CFC-11-Eq	Stratospheric chlorine and ozone-depleting substances: **Diminish the ozone layer and adverse effects on human healthiness and ecosystem quality.**	*5.08E-06*	*2.25E-07*	*22.57*
			Resource impacts			
6	Urban land occupation - ULOP	m2a	Focuses on land use impacts due to area alteration and damage to biodiversity; **Loss of agricultural land, species loss**	2.5	2.88	1.15

c) **EI Results**

The initial phase of controlling the negative ecological impact of products or services is to estimate the Environmental Impact (EI). Once the EI results are obtained, the LCA interpretation stage assesses the inputs, outputs, and associated emissions of the system. Moreover, sustainability indicators are obtained for each manufacturing operation, and their contribution to the resulting EI is evaluated and mapped. Fig. 6 presents the results obtained from comparing two STs, two LCIA methods, and six impact categories. Tab. 4 shows the results of the chosen impact categories. The impacts were characterized and normalized and then compared based on their maximum/minimum relative deviation (Rmax/min) across six impact categories [12]. Upon analyzing the available STs, it was noticed that the impact categories with the greatest relative impacts were ODP and FEP.

Tab. 5 revealed that among all, ReCiPe had the highest Rmax/min ratio in HTP, causing significant result deviations. However, ReCiPe showed negligible variation for GWP, leading to accurate results. It should be noted that GWP showed comparatively accurate results in ReCiPe and CML. This is due to each method possessing its specific weighing coefficient for impact scores and considering different elementary flows [42].

Table 5. Result comparison between ReCiPe and CML method

Impact category	**ReCiPe**			**CML**		
LCA software	**openLCA**	**GaBi**	$R_{max/min}$	**openLCA**	**GaBi**	$R_{max/min}$
HTP (kg 1,4-DCB-Eq kg)	15.8	5	3.16	21.87	7.76	2.81
GWP (kg CO2-Eq)	42.16	26.6	1.58	43.82	26.3	1.66

It was found that climate change had a significant impact in all two LCIA methods, but there was a difference in the values reported by GaBi (27kg CO2 eq) and openLCA (44kg CO2 eq) - this inequality was observed across all impact categories. The disparity in results could be due to calculation algorithms, including software design, programming, or data constraints. The CFs used by GaBi and openLCA may differ from those used by other software, leading to variations in the results.

(4) Interpretation

The choices made during process planning and design have a substantial impact on the product life cycle. This study can help practitioners and engineers understand the relationship between emerging technologies and their EI. The study has implications for environment-conscious decision-making in the tooling industry, particularly in selecting materials, processes, coolants, and toolings. From a lifecycle standpoint, the primary sources of EI are the extraction of raw aluminum and manufacturing on VMC, which generate significant GHG emissions. The results indicate that raw aluminum extraction and VMC manufacturing are the top contributors to the EI from a lifecycle perspective due to GHG emissions during metal extraction and machining. Lubricant and coolant waste, along with their fumes, also contribute significantly to overall impacts. As a result, IC tooling manufacturing generates various EI such as VOC, NOx, Sox, nanoparticles, cyanide, mineral oils, phenols, and heavy metals due to coolants, tool scrap, chips, fumes during metal cutting, coolant mist, raw material production, and production stages.

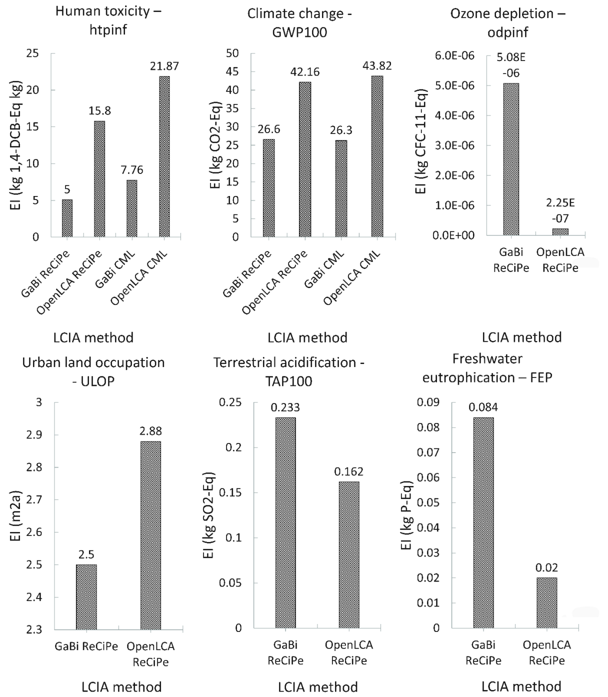


Fig. 6. Environmental impacts from turbine die production

Based on the relevant life cycle stages, processes, elementary flows, and impact categories, it is evident that the GWP for one piece of IC die is above 44kg CO2 equivalent (openLCA) and 27kg CO2 equivalent (GaBi) for both ReCiPe and CML. The major contributor to this impact is the electricity required for melting ingots, machining, and finishing operations. Although both ReCiPe and CML show little variance for this impact category, there is a significant deviation in the 'human toxicity' impact category between employed LCIA methods, indicating a difference in CFs for the respective impact category.

Hereby the process responsible for each impact category is similar between the two STs that are discussed. Terrestrial acidification is 0.162 kg SO2 eq (openLCA) caused by SO2 and NOx releases in the environment. For that, Al production, power generation, and transportation are the top three contributing processes in descending order. Freshwater eutrophication is mainly affected by waste treatment and disposal of non-hazardous waste like red mud from bauxite mining, spoil from lignite coal mining, hard coal ash, etc. Heat production in the industrial furnace to produce ingots, coal and aluminum mining, and electricity generation, transmission and distribution are the processes responsible in descending order for climate change. Human toxicity is primarily caused by waste treatment processes, hard coal ash, hard coal, and lignite wastages. Ozone depletion is caused by the extraction of fossil fuels and transport. Urban land occupation is affected by hard coal mining and waste treatment processes.

Reduction of EI

Material extraction and manufacturing represent the most significant phases contributing to Environmental Impact (EI) in the context of IC tooling manufacturing. A breakdown of the issue reveals key challenges as outlined below. Aluminum extraction involves significant consumption of power, water, and resources, while the melting of ingots requires substantial electricity. Manufacturing processes conducted on VMC have been associated with high embodied energy (measured in kWh/part), material wastage, elevated tooling costs, prolonged lead times, and challenges related to coolant disposal.

Addressing the root causes of these issues suggests potential strategies for reducing EI. Firstly, a shift towards remanufacturing or repairing rather than opting for new tool manufacturing could be beneficial. Alternatively, if new tool manufacturing is unavoidable, hybrid manufacturing techniques (using Additive Manufacturing) present a viable option. Optimizing cutting parameters and selecting the most efficient processing routes can result in lower scrap rates, reduced tool wear, and shorter lead times. Furthermore, on VMCs promoting the sharing of tools, maximizing machine utilization rates, and minimizing idle times can lead to significant reductions in EI.

3. Understanding Result Discrepancies

Fig. 6 displays noteworthy differences between GaBi and openLCA, as well as between the ReCiPe and CML methods. The primary factors that are accountable for these variances are outlined below [43-45].

Comprehensive database

Quality of data is necessary for consistency, completeness, accuracy, precision, and precision of inventory. In our case of tooling manufacturing aluminium ingot is employed as a row material. If we search 'aluminium ingot', we shell get various options like aluminium ingot manufactured by rolling, casting, or even recycling aluminium cans, etc. Even though the quantity is the same for raw materials but the choice of the ingot production process makes a huge difference in the results. In a few STs, there may be a proxy element or absence from the database which will lower the accuracy of the results [8].

LCI characterization

LCI data sets can either include all individual substances or just the main ones, resulting in either detailed or simplified EI calculations the same scenario is in openLCA and GaBi respectively. In addition, GaBi reports emissions to air, water, and soil, and material extraction emissions in the form of a table and chart whereas openLCA gives these data in the form of a table. Moreover, openLCA has greater linked processes than GaBi and that is the reason why it has a higher impact score. Practically, only a few processes or emissions actively contribute to the EI. The number of substances like HC, NO2, SO2, etc. is aggregated in the software which creates a discrepancy with the substance and sub-substance inventory data. Moreover, the variation in substance naming across different inventory datasets makes it difficult to determine the exact composition of substance categories, leading to double-counting errors [6], [7], [46].

LCIA method

Resultant EI depends on the choice of LCIA method which further depends on LCI data and this has a dependency on the number of tracked flows. Hence, the greater the tracked flows, the more accurate results will be. Besides, there are cases where GaBi possesses a CF for the CML/ReCiPe method while openLCA does not, or vice versa. Even if each software has a CF, the values may differ significantly. There are instances where the software uses zero due to differences in the spelling of substance and CF names.

Technical, temporal, and geographical representative

Temporal representativeness is the accuracy of the period being represented and is tied to technological representativeness. The concept of technological representativeness pertains to the degree to which inventory data accurately depict the genuine technical features of a system or procedure. Geographical representativeness takes into account environmental conditions and regulations in relevant regions. Ensuring these aspects in an LCA study improves result accuracy and reliability, aiding informed decisions on sustainability [47]. E.g., for electricity, low voltage there is valid data taken in 2016, on the energy produced from solar panels in the western region of India. Regarding aluminum ingot, GaBi displays a significant technological correlation, a moderate geographical correlation, and a low temporal correlation. On the other hand, openLCA exhibits high correlations in terms of technology, time, and geography for the same.

System Boundaries and Allocation Methods

The boundary of the studied system is set to ‘cradle to gate’. Here we are using foreground processes and background processes for system modelling. However, it is uncertain if the inventory data sets consider the EI of producing the energy sources required for the background processes linked to the foreground processes. Also, the exclusion of any process should be justified with cut-off criteria.

Process modelling approach

Model and parameter values differ depending on the ST which may calculate EI differently.

4. Stepwise Software Comparison

Software installation, database, and importing LCIA methods:

openLCA and GaBi are two STs used for LCA and sustainability assessment. openLCA can be easily downloaded from its website openLCA.org and GaBi is available from sphera.com (earlier thinkstep.com). Both STs are easy to install and run, and require a database to create flow, process, and product systems. Users can also create their own database according to their requirements. openLCA supports both free and paid databases, while GaBi supports only paid databases. LCIA methods are available freely in both STs. Currently, the ecoinvent 3.71 database is employed in openLCA and GaBi. To enable EI assessment, both STs require importing databases and LCIA methods.

Model creation

After importing the database into both openLCA and GaBi, users can create processes by clicking on the process tab. In openLCA, users can create processes by entering inputs and outputs, such as flow, category, amount, unit, and cost, avoiding waste, uncertainty, data quality entry, parameters, and provider. GaBi offers options such as parameter, flow, quantity, amount, factor, unit, tracked flow, relative deviation, and origin for creating processes. In both STs, flows can be searched and filtered, and GaBi users can drag and drop the correct flow. In both STs, if the flow is not present in the chosen database, users can add it manually by entering the flow type, amount, and units. Once all processes are defined, the next step is to create the product system. This involves selecting a reference process and linking the system/unit process and providers in openLCA, while in GaBi, the nature of the process and providers of flow can be defined during process creation. After creating a complete error-free product system, a model graph (openLCA) or plan (GaBi) of the connected processes can be viewed, which contains the depiction of the amount of energy and mass flows, process connections, and nature of processes. This is a visual representation of process modeling similar to a process flow chart. In our case, all employed processes are of unit type, and system-type processes are not used to avoid significantly divergent results. The subsequent step involves computing the results [48-51].

Results

When using GaBi software, the "Result" option displays the output inventory of general emission data, and clicking on "Diagram" provides a graphical representation. A new dashboard tab near the Result tab indicates LCIA method options, and after choosing an LCIA method, impact category-wise final results of EI are displayed process-wise in colorful bar charts. However, GaBi has limited LCIA method options available. In openLCA, after creating product systems, clicking on the "Calculate" option allows users to choose the allocation method, impact assessment method, and normalization and weighing set to display the complete result section. The result section includes a bar chart showing the top five impact indicators and flows, process contributions to EI, and impact category-wise results. Additionally, openLCA has the additional feature of showing a Sankey diagram and regionalized LCA of product systems. GaBi provides quick computation of results, while openLCA takes a few moments to minutes depending on the complexity of the product system. Both STs have the facility of sensitivity and uncertainty analysis and exporting results in the form of an Excel sheet. GaBi’s i-report module can generate reports for users utilizing embedded templates. Additionally, the weak point function is capable of identifying and highlighting the weakest point in the product life cycle within the results table. Overall, the GUI of GaBi is smooth and interactive, user-friendly, and the modeling is neat with fine details, but it lags in terms of database capacity and LCIA methods. On the other hand, openLCA has quick product definition creation, a sound result section, and supports rich database and LCIA methods, but lags in terms of GUI, result presentation, and calculation time [49], [51-53].

Software Tool comparison

Both GaBi and openLCA offer comprehensive LCA studies and allow users to edit the database, processes, or flows. However, GaBi boasts a user-friendly GUI and generates appropriate text and charts, while openLCA can sometimes display oversized or undersized text and charts. GaBi allows users to easily add inputs and outputs in a lifecycle builder, while openLCA offers a tabular data-feeding interface. GaBi generates a result presentation in the form of a bar chart showing all individual impact categories, while openLCA provides a bar chart indicating the top five flow contributors to a specific impact category.

Both STs offer the ability to set cut-off criteria and allow multiple users to access the database. GaBi offers quick results and easy switching between windows, while openLCA may take longer to compute and may slow down the device. GaBi has an area chart option showing the output inventory of general emission data like emissions to air, water, land, and seawater, with values of all these categories shown in kg. Which is available in openLCA under the ‘LCIA checks’ section with relevant units e.g., emissions to air, (kBq), emissions to water(m3), and emissions to soil (g). openLCA enables the depiction of the relative contribution of processes to the overall impact through a Sankey diagram visualization. Additionally, it includes the capability of regionalized LCA and LCC. Sensitivity analysis and Monte-Carlo simulation options are available in both STs to ensure data validity.

GaBi is a licensed software, while openLCA is an open-source LCA software; however, both support paid databases. Therefore, users must make informed decisions when selecting an ST for their study objectives. Some features of both STs may be missed during the comparison.

5. Conclusions

The following conclusions are derived from the case study conducted on conventional tooling manufacturing through the use of GaBi and openLCA.

- Each software supports enough databases that contain flows and processes to handle traditional tool manufacturing processes.
- The choice of the LCA ST governs results for specific applications and it varies significantly.
- The use of the same LCIA method, impact category, model, and input data results in divergent outcomes between GaBi and openLCA, likely due to changes in CFs and potential LCI database variations. However, both tools identify the same hotspots.
- The highest relative deviations were observed in ozone depletion potential (22.57) and freshwater eutrophication (4.2). The ReCiPe shows significant result deviations with the highest relative deviation ratio in human toxicity (3.16). While climate change (1.58 and 1.66) gives accurate results using CML and ReCiPe.
- Among both the software, GaBi has an intuitive user-friendly GUI, great modelling capability, and grants flexibility to a user which is highly recommended to new users while openLCA is cost-effective, comprehensive, and has better functionality suggested for experienced users.
- Based on the contribution, the primary focus of CM should be to reduce energy consumption by improving the processing steps and selecting appropriate machining parameters. This would involve identifying the most efficient sequence of steps in the manufacturing process and using cutting tools and settings that consume minimal energy. Aluminum production has the second highest impact on EI and is closely linked to the stage of material production and manufacturing. This issue could be solved by improving material utilization.
- In general, the selection of ST should depend on the particular needs and demands of the manufacturing procedure. The study's findings will help organizations select the most appropriate LCA software option based on their specific needs.

6. Future scope

The findings of this research paper provide a good foundation for further research in the area of LCA ST comparison for traditional tool manufacturing applications. Here are some potential areas for future research:

- The findings presented in this research paper lay a strong foundation for future research in the area of LCA ST comparison for traditional tool manufacturing applications. Several potential areas for further research have been identified. Firstly, while this study only compared two LCA STs and was limited to a single case study, future research could expand this by comparing a broader range of STs and including a wider range of product categories.
- Secondly, academia and industry should collaborate to develop a local LCI database that complies with national and international standards.
- Moreover, an independent authority should be established to certify and authorize the validity of LCA software. In case of faulty result reporting, the software provider should be held responsible rather than the LCA practitioner, as it is not feasible for the LCA expert to identify and rectify the flaws generated by the software.

Acronyms

software tools (ST); Investment Casting (IC); Sustainability Analysis (SA); Life Cycle Analysis (LCA); Life Cycle Costing (LCC); Social Life Cycle Analysis (S-LCA); Life Cycle Engineering (LCE); United Nations (UN); Conventional Manufacturing (CM); Triple Bottom Line (TBL); Specific Energy Consumption (SEC); Aluminum (Al); Life Cycle Inventory (LCI); Global Warming Potential (GWP); Vertical Machining Center (VMC); Environmental Impact Assessment (EIA); Life Cycle Impact Analysis (LCIA); Volatile Organic Compound (VOC); Green House Gas (GHG), Carbon Dioxide (CO2), Methane (CH4) and Nitrous Oxide (N2O), Characterization Factor (CF)

Acknowledgment: The authors are grateful to Mr. Vikram Thaida, Devanshi Engineering, Rajkot for granting access to their industry Devanshi Engineering to take experimental data.

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