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Implementing circular economy principles in micro heat sink development: A techno-economic-sustainability analysis

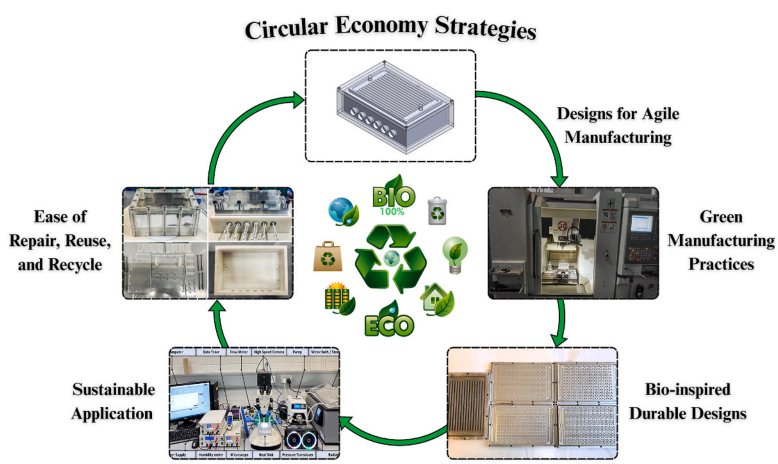
Mohammad Harris **, Hongwei Wu *

School of Physics, Engineering and Computer Science, University of Hertfordshire, College Lane Campus, Hatfield, AL10 9AB, UK

HIGHLIGHTS

- Introduces a hybrid circular manufacturing model for micro heat sinks.
- Achieves 42.76 % cost and 28.95 % energy savings.
- Validated outcomes using machine learning models.
- Proposes a new Sustainable Hybrid Intelligence Framework (SHIF).

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable manufacturing solutions are urgently needed with rising environmental pressures and cost volatility. This paper investigates sustainable product development strategies for micro heat sinks by integrating circular economy principles, emerging technologies, and green manufacturing practices. Analysing a UK–China cross-case hybrid production model, the study compares strategies in terms of energy efficiency, cost savings, and environmental impact. The hybrid approach balances economic, ecological, and resource consumption goals by producing simpler components in-house while outsourcing complex parts. Results show a 19 % reduction in carbon emissions, 29 % energy savings, and 43 % cost reduction. Sustainable design, green manufacturing, and end-of-life management further contribute to environmental benefits. Machine learning models validated the cost-saving outcomes, achieving R^2 values exceeding 0.98. Finally, the study proposes a Sustainable Hybrid Intelligence Framework (SHIF) to demonstrate the feasibility of hybrid manufacturing as a sustainable solution for future micro heat sink production.

* Corresponding author.
** Corresponding author.
E-mail addresses: m.harris8@herts.ac.uk (M. Harris), h.wu6@herts.ac.uk (H. Wu).

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Nomenclature

Abbreviation	Full Form
AM	Additive Manufacturing
CE	Circular Economy
DFMA	Design for Manufacturing and Assembly
EPR	Extended Producer Responsibility
JIT	Just-In-Time Manufacturing
MCH	Micro Heat Sink
MEDS	Materials, Enhanced Flow, Design, and Sustainability
ML	Machine Learning
PDMS	Polydimethylsiloxane
PMMA	Polymethyl Methacrylate
RF	Random Forest
RMSE	Root Mean Squared Error
SDGs	Sustainable Development Goals
SHIF	Sustainable Hybrid Intelligence Framework
TQM	Total Quality Management

1. Introduction

The increasing miniaturisation of electronic devices and the rising power densities in applications such as computer chips, data centres, electric vehicles (EVs), and aerospace systems have heightened the need for sustainable thermal management solutions. Due to their high surface-area-to-volume ratios, micro heat sinks are critical in addressing this challenge. However, traditional single-fabrication methods—such as CNC machining and chemical etching—are often associated with significant material wastage, substantial energy consumption, and high production costs (Tsao et al., 2020). These inefficiencies underscore the necessity of adopting more sustainable manufacturing and production resource consumption practices.

The circular economy (CE) offers a viable alternative to conventional linear production models by prioritising resource efficiency, waste reduction, and reusability (Cagno et al., 2025). Although Circular Economy (CE) has its roots in *Cleaner Production*, CE represents a more transformative approach that seeks to eliminate linear resource flows by promoting closed-loop systems focused on regeneration, reuse, and reliance on renewable materials (de Oliveira et al., 2022, 2023a). This reformative approach aligns with key global sustainability initiatives, including the European Union's Green Deal, the United Nations' Sustainable Development Goals (UN SDGs), and the UK's Net Zero Strategy, advocating for sustainable consumption patterns (Ee et al., 2024). Simultaneously, Industry 4.0 technologies—such as automation, machine learning, and real-time analytics—transform manufacturing processes by enabling precise process control, minimising variability, and facilitating reduced product development times (Frank et al., 2019; Harris et al., 2020). Thus, integrating CE principles with the latest technology provides opportunities for technology-driven continuous improvement to optimise production efficiency (Harris, 2021) and resource utilisation while reducing long-term environmental impact (Pan et al., 2024).

Furthermore, established product development and manufacturing philosophies—such as Lean Manufacturing, Six Sigma, Agile Manufacturing, and Design for Manufacturing and Assembly (DFMA)—offer systematic approaches to improving performance (Harris et al., 2025), cost-effectiveness (Harris et al., 2024) and sustainability-driven product development (Costa et al., 2024; Rathi et al., 2022). Design for the Environment (DfE), in particular, promotes sustainable product development by minimising environmental impact across a product's life cycle through the optimisation of materials, energy use, durability, recyclability, and safety, thereby supporting sustainable design and regulatory compliance (De Paoli et al.). This can be achieved through Lean Manufacturing, which minimises material waste and resource consumption; Six Sigma, which enhances precision in complex geometries and reduces waste; and Agile Manufacturing, which enables rapid design iterations and development.

Despite the growing interest in sustainable engineering and manufacturing (Zuo et al., 2025; Garetti and Taisch, 2012) in different sectors, through strategies such as production planning and control to enhances eco-efficiency and reduces environmental impact (de Oliveira et al., 2016), or cleaner production highlighting both environmental and economic benefits of recycling (de Oliveira Neto et al., 2015), research that holistically integrates cost efficiency, environmental impact, and technological advancements within micro-manufacturing remains limited. Moreover, studies examining the environmental and economic aspects of micro heat sink production are also scarce. While Quo et al. (Gao et al., 2016a, 2016b) conducted economic and environmental assessments of microchannels, and Mathiyazhagan et al. (2022) explored framework for implementing sustainable lean manufacturing in electronic components, few studies adopt a comprehensive integrated approach to sustainable manufacturing. Furthermore, although some works investigated green manufacturing initiatives (Liu et al., 2023), integrated philosophies (Eskandari et al., 2022), they seldom provided a thorough evaluation of circular economy strategies within the micro-manufacturing sector or for thermal management systems, potentially due to a lack of knowledge in this area (Cagno et al., 2023).

Additionally, most studies assume a single-location production model, either in high-cost regions such as Europe or in lower-cost, high-volume manufacturing hubs like China (Cheng et al., 2025). However, limited or no research has explored a hybrid manufacturing strategy that strategically distributes production across these regions to optimise both cost and sustainability. Furthermore, the absence of predictive models for assessing cost-sustainability trade-offs at scale further limits manufacturers' ability to make informed, data-driven decisions in energy or thermal systems.

Building on existing research, this study aims to bridge key gaps by integrating circular economy principles, manufacturing philosophies, and predictive analysis into micro heat sink development. The focus is on optimising cost efficiency and process sustainability while leveraging methodologies like Lean Manufacturing, Six Sigma, Agile Manufacturing, and DFMA to enhance quality, cost-effectiveness, and scalability.

To assess the practicality of different production strategies, this study compares the cost and sustainability of two distinct manufacturing models. The first is a fully UK-based approach, where in-house production relies on local CNC machining. While this ensures high-quality control, manufacturing complex geometries in the UK is significantly more expensive due to high labour and operational costs. The second is a hybrid model, strategically splitting production—simpler geometries are manufactured in the UK to leverage local expertise and rapid prototyping, while more intricate designs are produced in China to capitalise on cost-efficient, high-precision manufacturing. Moreover, machine learning models were developed to predict cost benefits at scale, assisting in optimising resource allocation and making more informed decisions.

The contributions of this study are presented across several key sections. Section 2 reviews existing research trends to identify best practices in micro heat sink manufacturing, providing a foundation for comparison and collaboration. In Section 3, the study evaluates the integration of circular economy principles into micro-manufacturing, focusing on sustainability and resource optimisation. Section 4 offers a comprehensive comparison of different production models for micro heat sinks, using Techno-Economic Comparison (TEC) and sustainability analyses to assess both cost and environmental impacts. Additionally, the study leverages machine learning to develop a predictive model that assists manufacturers in scaling production sustainably. Lastly, a novel decision framework is proposed, leveraging established manufacturing philosophies and providing actionable insights for industry stakeholders. By addressing the intersection of cost, sustainability, and advanced manufacturing strategies, this study offers an integrated approach to enhancing micro-manufacturing practices while contributing to global sustainability goals.

2. Current state-of-the-art

In the introduction section, a thematic analysis identified the initial research gaps at the intersection of circular economy principles and sustainable micro heat sink development, particularly in hybrid manufacturing and philosophies. This thematic analysis provided insights into the limited integration of these concepts, guiding the selection of keywords for a more rigorous investigation. To enhance the scientific depth of the study and establish a robust foundation for the research gap, a comprehensive keyword-based literature search was performed using the Scopus database. An initial search combining the terms "circular economy" and "sustainable product development" over the past 15 years yielded over 5100 results. A funnelling approach was then applied, to narrow down and prioritise studies relevant to thermal management applications, and focus on domains such as thermal management, heat sinks, and microchannels, which significantly reduced the number of applicable studies to 78, 1, and 0 results, respectively. To further investigate the gap in the specific context of micro heat sinks manufacturing, an additional search using the keywords "heat sinks" and "thermal management" produced approximately 4123 results. These key terms were then paired using terms such as "hybrid manufacturing," "green manufacturing," and "sustainable manufacturing," narrowing the pool to only 28, 6, and 8 papers, respectively. Therefore, using both thematic and keyword analysis, the gap in this area was evident.

To visualise the state of the art and gain a initial understanding of current research trends that could be improved upon or extended, a co-occurrence network diagram was generated. This analysis was based on the abstracts, titles, and keywords of the selected publications. As illustrated in Fig. 1a, the network revealed that research related to the circular economy is predominantly concentrated in biomedical, plastic recycling, and lifecycle assessments. In contrast, Fig. 1b showed that studies in the field of heat sinks are primarily performance-oriented, with limited consideration of sustainable manufacturing practices. This scoping review approach further confirmed the relevance of investigating circular economy-informed hybrid manufacturing strategies for advanced thermal management applications, particularly in micro heat sinks.

Furthermore, a review of the extant literature reveals a gap in comprehensive studies assessing micro heat sink (MCH) fabrication and product development methods in detail. While existing research categorises data on shapes (Du and Hu, 2023), working fluids (Harris et al., 2022), fabrication (Kandlikar and Grande, 2003), amongst other, identifying overarching trends is complicated due to various factors. Therefore, this study expands on the data of our previous works (Harris et al., 2022) to provide a more recent perspective of the current research space, taking data from papers between 2017 and 2024. It evaluates key trends in MCH research and development, aligning with the MEDS framework and integrating sustainability and circular economy principles. The trends will help making data-informed decisions related to the type of materials, fabrication processes, collaboration, working fluid choice, methods, amongst others.

Therefore, expanding on our previous study, data from 100 papers were analysed, categorising MEDS elements such as fabrication strategies, material choices, and geographical distribution of micro heat sink (MCH) research to identify potential knowledge exchange and research collaboration opportunities highlighted in Fig. 2a–(g). For the purpose of brevity, only the main or top trends were analysed. Geographical trends (Fig. 2a) indicate that China (44 %) and the rest of Asia (23 %) dominate MCH research, comprising two-thirds of global contributions. Europe, with an 18 % share, contributes modestly despite MCH technology's alignment with the EU's 2050 climate (Tol, 2021) and UN Sustainable Development Goals (SDGs) (Zaidan and El Fadel, 2024). Limited research output from regions like Africa and South America may stem from funding or resource constraints. Thus, increasing MC research via different perspectives, such as this study, could significantly enhance sustainable engineering, promoting more efficient resource use.

Assessing design trends (Fig. 2b) is crucial in advancing MC technology. Rectangular MCs have been predominant over the past seven years due to their dependability and ease of fabrication. However, emerging innovative designs like spiral or curved channels (12 %) and complex shapes like bio-inspired/hybrid designs are gaining traction. In terms of MC fabrication methods (Fig. 2c), the processes can significantly influence performance and sustainability. Micromachining (31 %) remains the most common method, with lithography rising and etching declining. Additive manufacturing (AM), especially 3d printing, offers sustainable advantages by reducing material waste. The fabrication process's lifecycle impact can be pivotal; adopting energy-efficient, green manufacturing and recyclable materials supports circular economy principles, minimising waste and extending product lifecycles. Hydraulic diameter and aspect ratio (Fig. 2d and g) play critical roles in MC performance. Smaller hydraulic diameters (<500 μm) improve heat transfer efficiency but complicate manufacturing, while high aspect ratios enhance heat dissipation but may produce high-pressure drops and energy/power usage. Hence, MC designs must optimise these parameters to balance performance, manufacturability, and material efficiency.

Material and fluid selection trends (Fig. 2e and f) highlight the need to align choices with circular economy objectives. Commonly used MC fabrication materials include polymers (PDMS, PMMA) and metals

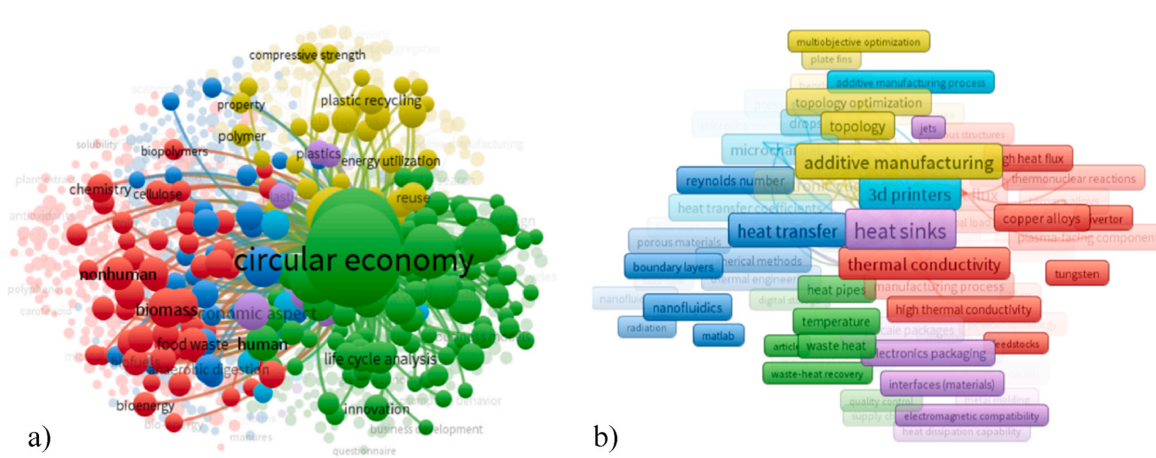

Fig. 1. (a)–(b): Co-occurrence network map for research trends.

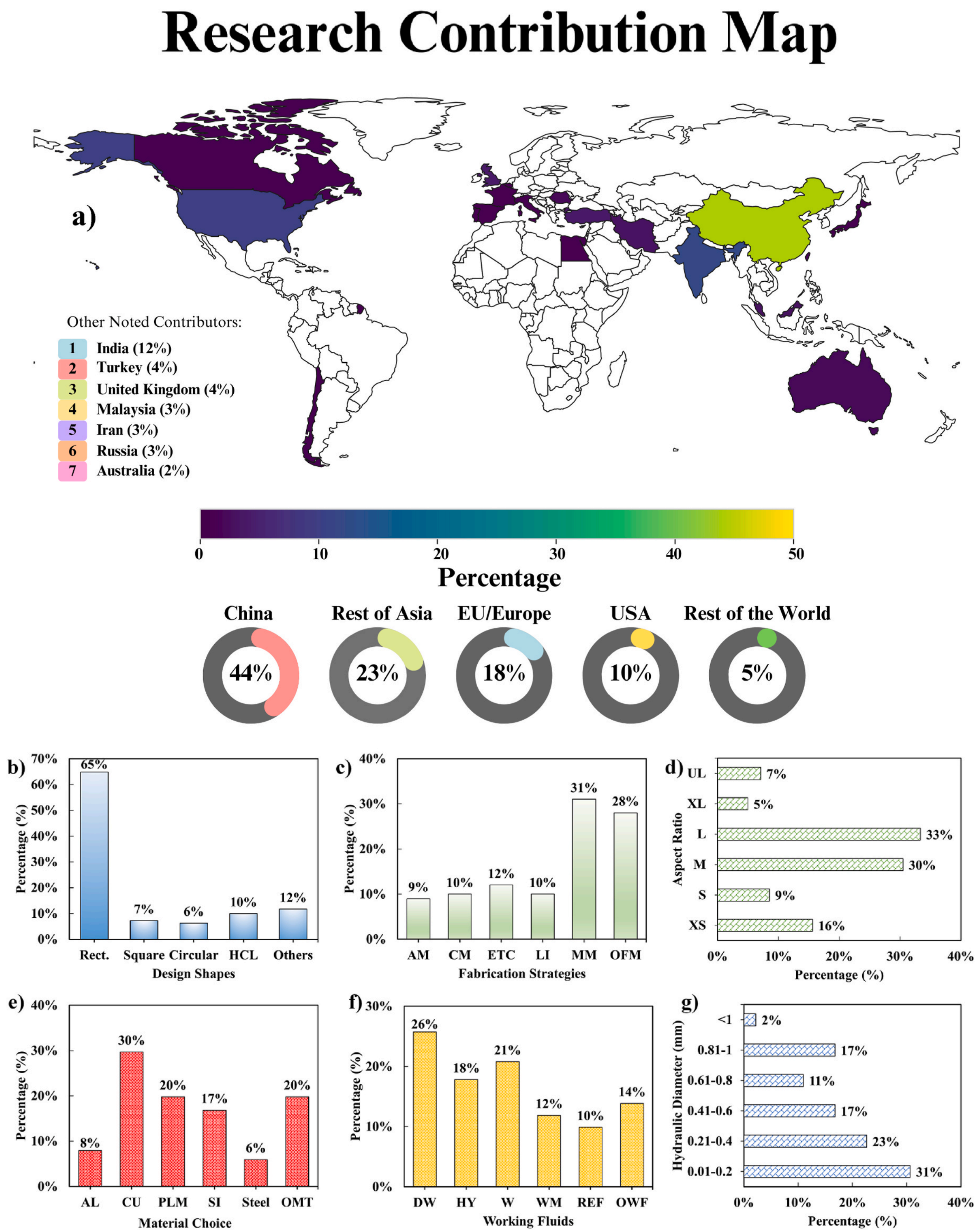

Fig. 2. (a)–(g): Overview of recent trends in micro heat sink fabrication.

(copper, silicon, aluminium, steel) (2e). Metals offer high thermal conductivity but have substantial environmental footprints and can be hard to machine (such as copper). Polymers are lighter and cost-effective but often lack recyclability. Future research should explore bio-based, recycled, or composite materials.

Water and water-based solutions are the predominant experimental working fluids (Fig. 2f), with de-ionized water (DW) as the preferred choice. Hybrid nanofluids incorporating metals like aluminium, copper, and silver offer enhanced thermal properties but pose environmental challenges like nanoparticle toxicity and disposal. Investigating biodegradable and recyclable alternatives is crucial. Refrigerants such as R134a and HFE-7100 are also used due to their high heat transfer coefficients and low boiling points. However, the high global warming potential (GWP) of R134a and the environmental persistence of HFE-7100 raise sustainability concerns (Nair, 2021). In line with circular economy principles, there is a push towards using low-GWP alternatives to mitigate environmental impact. Thus, water remains a good, sustainable working fluid option.

Appraising the literature, it can be noted that to drive sustainability in MCH research, a shift from current practices is essential. Hence, *To drive sustainability in micro heat sink (MCH) research, future work should focus on:*

Material Circularity: *Recyclable (*e.g., *aluminium alloys), multipurpose, high-strength, or bio-based materials (*e.g., *polylactic acid) should be developed to enable reusability or biodegradation, thereby reducing material waste and addressing high-impact resource use in line with circular economy principles.*

Eco-Friendly Fabrication: *Sustainable manufacturing approaches, such as green manufacturing (low energy consumption) or additive manufacturing techniques, can be employed to produce efficient MCH designs with reduced waste and energy demands,* supporting *cleaner production and hybrid manufacturing strategies.*

Green Working Fluids: *The selection of low-GWP fluids or suitable alternatives to R134a and HFE-7100 for maintaining thermal performance while significantly reducing emissions, contributing to environmental sustainability.*

Techno-Sustainability Gap (TSG) and Techno-Economic Comparison (TEC): *Machine learning and dynamic life cycle assessment methods can be applied to assess sustainability gaps and perform comparative analyses of cost and emissions. This enables the development of cost-effective, environmentally sustainable, and intelligent MCHs, fostering continuous improvement through technology integration.*

Embedding circular economy principles in MCH research will create technologies that meet performance demands while advancing global sustainability goals (Yadav et al., 2023). Focusing on material and cost efficiency, energy conservation, and waste minimisation is crucial for sustainable MCH-based technologies in manufacturing and environmental impact improvement, alongside enhancing global research collaborations between developed and emerging economies— aligning with both circular and sustainable development goals (de Oliveira and Oliveira, 2023).

3. Heat sink fabrication

Life cycle assessment (LCA) is a significant tool that quantifies environmental impacts and effects of products (Pryshlakivsky and Searcy, 2013); for instance, LCA can identify high-impact phases, such as machining, to inform emissions reduction. Life cycle assessment (LCA) data indicate that the majority of the environmental impacts occur during product manufacturing (Kuo et al., 2022), with material processing and machining being the primary contributors (Zikulnig et al., 2025). Table 1 outlines a systematic implementation of circular economy strategies across product lifecycle stages and beyond, showing how disassembly-ready designs and closed-loop material recovery can address these impacts. Table 1's strategies were developed to target not only LCA-identified high-impact manufacturing phases, but also additional phases, ensuring a holistic, sustainable MCH product development through circular economy principles without sacrificing thermal efficiency and performance.

We opted for a hybrid manufacturing approach. The heat sink fabrication process adopted a 3-axis milling approach for rapid prototyping, aligning with the Design phase's circular economy (CE) strategy of design for manufacturability and disassembly (Table 1). While this method highly complex geometry, it enabled iterative optimisation of thermal performance and modularity, key to extending product lifespan and simplifying future repairs. The simplified geometries also facilitated experimental validation, allowing rapid testing of design iterations under controlled conditions.

Local material sourcing and manufacturing prioritized recycled aluminium for basic components, significantly reducing embodied carbon and energy compared to virgin material (Peng et al., 2019), while complex geometries were produced through green manufacturing partnerships in China (renewable energy-powered and low power consumption-based CNC/machining facilities). In-house fabrication of micro/minichannels reduced costs and waste, supporting Local Resource Utilisation goals, though outsourced pin-fin production highlighted the persistent trade-offs between precision manufacturing and logistical emissions in global supply chains.

Surface treatment (alcohol polishing, Scanning Electron Microscope-verified consistency) addressed Usage-phase strategies by enhancing longevity through corrosion resistance (Table 1). However, the reliance on outsourced components underscored gaps in End-of-Life recyclability planning, particularly for non-aluminium parts (e.g., resins), as noted in the table's Challenges column. Quality assurance employed digital microscopy to validate surface integrity, linking to Enablers: Data Tracking by ensuring traceability. Yet, the absence of embedded QR codes or material passports limited post-use recovery potential, echoing the table's identified barrier of tracking system complexity.

Fig. 3 outlines the key stages of product development, beginning with Design Concepts (CAD modelling and iterative refinements for manufacturability and circularity); the Fabrication phase transforms these designs into physical prototypes, followed by Final Products

Table 1
Circular economy implementation across key product development stages.

Lifecycle Stage	CE Strategy	Implementation	Outcomes & Benefits	Opportunities & Challenges
Design	Design for durability and disassembly	Use CAD to optimise geometry, modularity, and disassembly	Extended product life, easier to upgrade or repair	Standardisation of components, but early design constraints may limit modularity
Enablers: Digital Modelling & ML	Forecast sustainability metrics and cost savings	Use ML to predict cost, emissions, and optimise design	Data-informed and iterative decisions in early stages	Requires robust data, integration with CAD workflows, but need for validation models
Material Sourcing & Manufacturing	Use recycled/sustainable materials, minimise waste	Sourcing. Use mix of CNC and AM to reduce waste	Reduced emissions, less virgin material use, better precision	AM reduces waste but has high energy use; AL over CU provides ease of machining
Local Resource Utilisation	Reduce transportation emissions	Source materials and machine components locally	Lowered logistics carbon footprint	Limited specialised material availability; potential for stronger supplier networks
Circular Material Flows	Reuse and reprocess materials	Investigate secondary materials in AM processes	Rigid 10K highly durable; supports closed-loop systems	Material variability in recycled inputs; quality control requirements
Usage	Improve performance and longevity	Use deionised water as a clean, low fouling working fluid	Stable thermal performance; extended component life	Explore smart fluid options; thermal efficiency gains have a limit.
Maintenance & Repair	Enable ease of repair and refurbishing	Disassemble parts easily; provide standardised kits	Reduces product replacement frequency; prolongs lifecycle	Requires user training and design-compatible repairability
End-of-Life	Promote recyclability and take-back schemes	Label parts for separation and tracking, with 85 % recyclability targets for product development.	Closes material loop; enhances CE goals	Resin/plastic recycling difficult; need for material-labelling standards and alternative use cases.
Enablers: Data Tracking	Improve traceability	Cloud-based storage/tracking	Accessibility to support agile decisions; EPR schemes	Cost, system complexity, and data privacy/security concerns
Enablers: Collaboration	Support ecosystem-wide circularity	Work with recyclers, suppliers, and policy bodies	Strengthens local and global circular supply chains	Requires strong coordination and shared platforms/research interests.

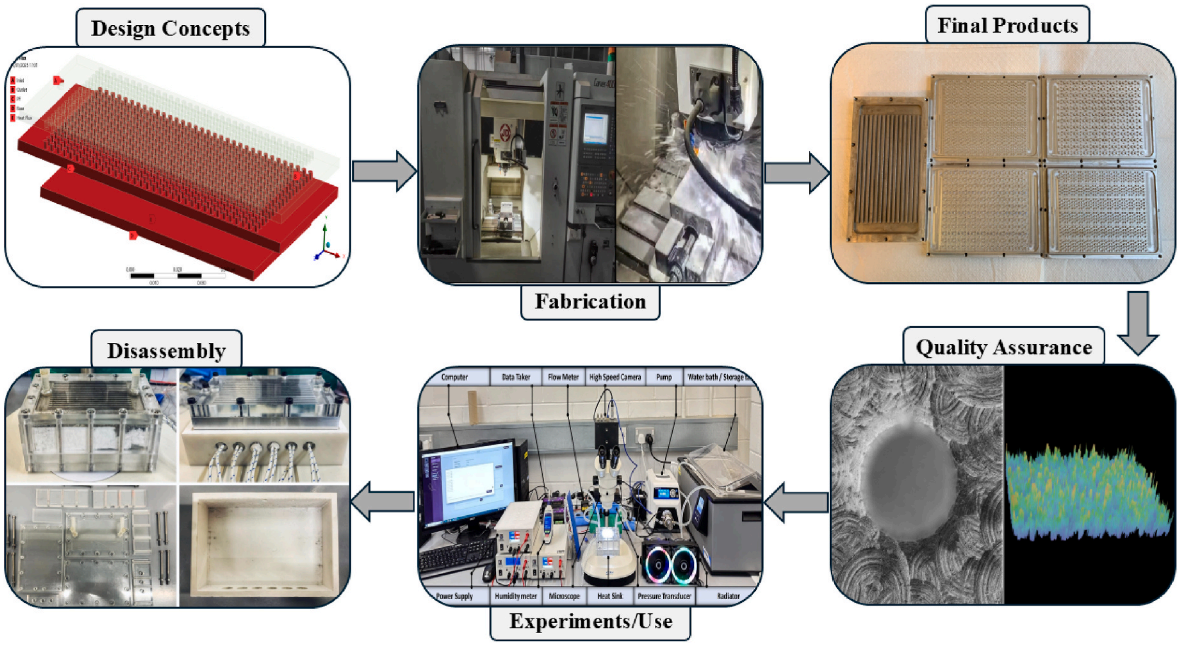

Fig. 3. Key stages of micro heat sink development.

(completed designs ready for fabrication). Quality Assurance ensures functional and sustainability standards are met before the Experiments/ Use stage, which validates performance (e.g., thermal testing) under real-world conditions and mimics usage. Disassembly emphasizes modularity and repairability; for instance, the reusing materials and setup for a new design, working fluid, or heat fluxes. This structured workflow demonstrates how circular economy principles are integrated at each phase without compromising functionality.

4. Techno-economic and sustainability analysis

To assess the impact of the hybrid manufacturing strategy, which involved producing simpler components in-house in the UK and outsourcing the complex parts to China, a comprehensive analysis was conducted. This approach was selected over fully producing in either the UK or China to balance cost, efficiency, and sustainability. Fully producing in the UK would result in higher costs due to expensive machining and labour rates, while full production in China would lead to potential bottlenecks and extended shipping times, contradicting the principles of Just-In-Time (JIT) manufacturing. By producing simple parts locally, we were able to leverage JIT philosophies, ensuring that only necessary quantities were manufactured without overstocking, thus reducing lead times and minimising storage costs. Additionally, the hybrid approach allowed us to retain tighter control over quality for critical components while taking advantage of green manufacturing from the manufacturer and cost benefits for more intricate parts. Another advantage of this hybrid strategy is improved flexibility in managing production changes, enabling a more agile response to market demands and design modifications without significantly disrupting the supply chain.

To ensure the accuracy and reliability of our cost assessments, we consulted and conducted semi-structured interviews with in-house manufacturing experts and external collaborators to gather different types of data (such as energy usage, material recyclability, etc.) and obtain multiple cost estimations from both sides. We chose a neutral USD to match the internal market trading standards. This consultation provided insights into machining costs, processing times, shipping rates, and material expenses. Further, we cross-checked these findings with data from the literature and credible online sources to validate the main parameters such as machining time, energy consumption, and carbon emissions. The integration of both primary and secondary data sources helped us form a robust basis for calculating overall estimated production costs and environmental impacts, ensuring that conclusions were well-founded.

4.1. Main parameters driving costs

Based on the semi-structured interviews with in-house (UK) and collaborators in China, we identified the main factors influencing production costs. Each region's cost drivers were carefully assessed and optimised as much as possible. For example, in the UK, no shipping costs were added as components were produced and assembled locally, whereas shipping costs were factored in for complex parts produced in China. Additionally, despite adopting green manufacturing options to reduce energy usage intensity, the production in China still resulted in slightly higher CO_2 emissions per kWh compared to the UK. This discrepancy is mainly due to the region's energy grid relying on higher proportions of fossil fuels (Lei et al., 2025). Consequently, we finalised the following as the primary parameters driving production costs and created a Pandas data frame to model our analysis. The following equations serve as a guideline for identifying key cost-driving factors, with parameters selected and tailored based on insights from related similar studies (Thomas and Gilbert, 2014; Dierkes and Siepelmeyer, 2019; Mickovic and Wouters, 2020). This was subsequently converted into a Pandas Dataframe for use in the study, implemented using Python in Google Colaboratory.

Total Cost Equation (Per Unit)

$$C_{\text{total}} = C_{\text{material}} + t{\cdot}L + E{\cdot}P + S$$

Variables.

- C_{material} : Material cost per unit (aluminium, location-dependent).
- : Machining time per unit (hours).
- L: Labour cost rate (£/ hour, location-dependent: L_{UK} or L_{China}).
- E: Energy consumption per unit (kWh).
- : Energy price (£/kWh, location-dependent: P_{UK} or P_{China}).
- S: Shipping cost per unit (£, only for Hybrid: $S = 0$ in Full UK).

For N Units:

$\text{Total}_{\text{Cost rum}} = N \cdot C_{\text{total}}$

Production Strategies.

1. Full UK: $S = 0$ (No shipping).
2. Hybrid: Include $S > 0$.

A 1000-unit production benchmark was followed as a standard unit for scalability and cost assessment (Tierney et al., 2021). This approach is commonly used in the industry to evaluate development and manufacturing costs, providing a consistent basis for comparing different production strategies. These parameters provided a comprehensive view of cost dynamics, enabling us to systematically assess the impact of varying production strategies.

4.2. Impact assessment and machine learning predictions

The comparison of the full UK Production with the hybrid production strategy revealed substantial benefits. The detailed calculations showed that switching to hybrid production resulted in a cost savings of 42.76 %. The energy consumption was reduced by 28.95 %, corresponding to a savings of 1100 kWh, while carbon emissions were lowered by 18.80 % (150 kg CO_2). These savings were visualised using the bar chart in Fig. 4a, which highlights the relative impact of each savings category.

The enhanced visualisation highlighted the cost savings driven by lower machining and material costs in China for complex pin-fin structures, while energy savings were achieved by utilising China's less energy-intensive green manufacturing processes for these parts. The carbon emissions reduction, although not as significant as the cost savings, still demonstrates the hybrid strategy's positive environmental

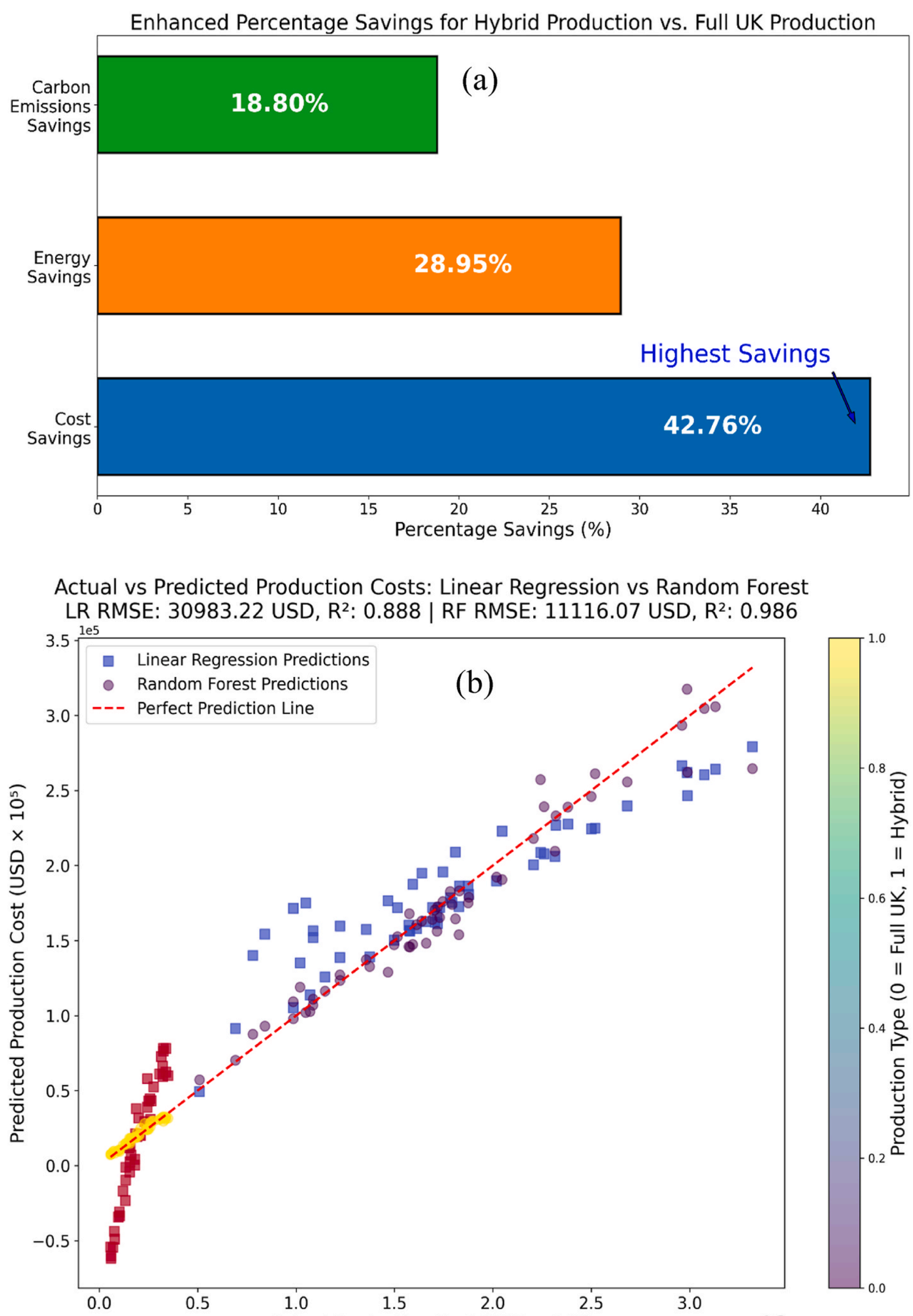

Fig. 4. (a) Savings for different categories; **(b)** Cost predictions.

impact, aligning with sustainable manufacturing goals. The hybrid approach thus effectively balances economic and environmental performance, making it a viable solution for the production of micro heat sink-related product development.

Moreover, the strategy aligns with broader sustainability objectives. By localising production of simpler components and reducing the overall energy demand in manufacturing, this approach supports circular economy principles and contributes towards the UN Sustainable Development Goal 12: Responsible Consumption and Production. It encourages more efficient resource use, lowers emissions in logistics and processing, and enhances responsiveness to changes in demand—an important factor in achieving long-term manufacturing resilience.

To further evaluate the impact of the hybrid strategy, machine learning techniques were employed to compare predicted production costs with actual values. A synthetic model comprising 500 data instances was generated by systematically varying key cost parameters. For example, machining labour costs were sampled between £20 and £50 per hour, depending on worker experience, while aluminium prices were varied by 20–25 % to simulate market fluctuations. This approach provided a robust, data-driven framework capable of adapting to dynamic manufacturing conditions. Subsequently, two machine learning models—Linear Regression (LR) and Random Forest (RF)—were trained to predict production costs using features such as units produced, production type, machining costs, labour rates, and material expenses etc. Model performance was evaluated using Root Mean Squared Error (RMSE) and the coefficient of determination (R^2), providing quantitative measures of predictive accuracy.

The Linear Regression (LR) model achieved an RMSE of 30,983 USD and an R^2 of 0.888, indicating that it captured general cost trends but struggled to model the complex variations. In contrast, the Random Forest (RF) model showed significantly better performance, with an RMSE of 11,116 USD and an R^2 of 0.986, demonstrating its ability to account for non-linear relationships and interactions between different production factors. Models were evaluated using an 80/20 train-test split, which helped ensure robust performance and prevent overfitting. The strength of the Random Forest predictions—closely aligning with actual values—adds further confidence to the hybrid production strategy and its scalability potential.

The initial cluster of points for Linear Regression at the start denotes the same type of random initialisation for the type of production happening, that is, 0 (full UK) or 1 (hybrid), and it is not an issue. Fig. 4b shows the visualisation of “Actual vs. Predicted Costs” using both models, and it further validates the chosen hybrid approach. The Random Forest predictions were clustered closer to the perfect prediction line, confirming the model’s reliability in capturing the cost dynamics of the hybrid production strategy. The strong predictive performance of the machine learning model thus reinforces the feasibility and effectiveness of hybrid manufacturing, supporting the decision to adopt this strategy over full local or outsourced production.

Overall, the hybrid strategy reduced costs, improved sustainability, and enabled agile and efficient production management. This approach leveraged data-driven insights, expert consultation, and rigorous verification using machine learning to evaluate the manufacturing process comprehensively. The resulting savings and environmental benefits made the hybrid production strategy an optimal solution for micro heat sink production, aligning with both economic and sustainable manufacturing objectives.

5. Integrated Sustainable Hybrid Intelligence Framework for product development

The development of the hybrid micro heat sink was underpinned by a systematic and integrated application of established manufacturing philosophies, with each principle contributing to the project’s cost-effectiveness, quality assurance, and environmental performance. To ensure replicability and scientific rigour, the framework adopted systematic protocols, inspired by eco-efficient production planning and control (de Souza Costa et al., 2021), Industry 4.0-driven circular economy strategies (de Oliveira et al., 2023b), and combined manufacturing philosophies (Harris, 2021), to develop a stage-by-stage methodology for the Sustainable Hybrid Intelligence Framework (SHIF). These protocols guided the synthesis of eco-efficiency and best practices, ensuring a structured, reproducible process for integrating circular economy principles across the product development stages.

Stage 1 (Research and Design): Following the systematic review protocols, Design Thinking and Sustainable Engineering were applied to understand heat sink requirements and assess low-carbon footprints. Lifecycle data validated the modular architecture for multiple heat fluxes and coolant types. In the conceptual phase, Design Thinking informed the creation of a versatile heat sink architecture capable of handling both single- and two-phase flow regimes. This flexibility reduced the need for multiple product variants, thereby lowering material demand and simplifying logistics and assembly workflows—an outcome aligned with sustainable product diversification.
Stage 2 (Prototype Development): Six Sigma and Agile Manufacturing facilitated prototype development, with precision control reducing waste and rapid prototyping enhancing process flexibility. A UK-China feedback loop enabled iterative design adjustments, with performance metrics documented for reproducibility. This facilitated fast adaptation to design modifications and performance improvements. For full-scale production and quality assurance, Six Sigma principles were implemented through the DMAIC (Define, Measure, Analyse, Improve, Control) framework. This ensured process reliability and continuous improvement, particularly in managing machining tolerances and minimising rework.
Stage 3 (Design Optimisation): Design for Manufacturing and Assembly (DFMA) simplified component geometry, achieving an 8 % reduction in material waste, while cost-effective assembly strategies were validated using computer-aided-engineering (CAE) tools such as CATIA and SolidWorks. This facilitated easier, faster machining and reduced tooling complexity, and, ensured a design that was efficient, cost-effective, and production-ready from the outset.
Stage 4 (Production Planning): Supply chain and production planning benefitted from Just-In-Time (JIT) manufacturing. Simpler parts were produced locally on demand, while complex components were batch-manufactured in China. This hybrid approach reduced inventory overheads and eliminated the risks associated with overproduction, procurement, overstocking, or obsolescence, supporting efficient, demand-driven manufacturing.
Stage 5 (Manufacturing): Lean Manufacturing optimised CNC toolpaths, reducing raw material offcuts by 15 %, and Green Manufacturing utilised eco-friendly materials and energy-efficient processes. Outsourcing intricate parts to a certified green manufacturer in China employed low-energy machining and closed-loop recycling, with data-driven machine learning methods quantifying the carbon and energy-intensity reduction despite regional disparities.
Stage 6 (Quality Assurance): Total Quality Management (TQM), continuous improvement (Kaizen), and quality checks, ensured machining tolerance reliability. In controlled experiments, sample production were tested to make the process replicable and reduce potential defects.
Stage 7 (Testing): Agile Manufacturing supported design performance testing and iterative validation, with the iterative thinking and feedback loop refining Stages 2–6 based on test outcomes. Documented testing protocols ensured adaptability and reproducibility.

To close the material loop, sustainable manufacturing practices repurposed aluminium offcuts into secondary applications, reducing virgin material use by 20 % and aligning with circular economy objectives. Each stage leveraged simulations, empirical cost modelling, machine learning predictions (e.g., Random Forest, $R^2 = 0.986$, RMSE = 11,116 USD), and collaborative digital platforms, grounding decisions in quantifiable metrics. Wherever applicable, we attempted to align our strategy with ISO 14006 (Environmental Management Systems – Guidelines for Incorporating Eco-design) (Arana-Landin and Heras-Saizarbitoria, 2011), mirroring its lifecycle thinking and environmental integration principles. Fig. 5 illustrates the systematic integration of these methodologies, showing how each stage embraced different manufacturing philosophies to enable cost optimisation, quality control, and promote sustainable product development within the SHIF framework.

6. Critical discussion

This study presents a novel and data-informed framework for hybrid manufacturing that advances the integration of sustainable production, cost-efficiency, and technological intelligence in the fabrication of microchannel heat sinks. The core attempt of this research was to bridge the often-ignored aspects of circular economy (CE), lean manufacturing, and machine learning within a hybrid sourcing context, guided by ISO 14006 eco-design principles. Consequently, the study findings have several novel contributions.

Firstly, the hybrid manufacturing strategy with circular economy alignment, by producing simpler components locally in the UK and outsourcing complex ones to a green-certified manufacturer in China, we developed a hybrid model that optimises cost without compromising environmental goals. This approach significantly outperformed traditional single-location models, achieving 43 % cost savings, 29 % less energy usage, and 19 % CO_2 reductions, while enabling agility and flexibility in response to design iterations. This is critical in a post-pandemic, geopolitically volatile era, where single-site dependency increases systemic risk. Our hybrid strategy improves supply chain resilience while reducing environmental externalities, directly supporting SDG 12 (Responsible Consumption and Production).

Secondly, multi-philosophy manufacturing, this research is the first to systematically apply a suite of manufacturing philosophies—including Lean, Six Sigma, Agile, DFMA, TQM, JIT, and Sustainable Engineering—mapped across each stage of product development. These were not applied in isolation but integrated into a coherent system informed by real-time data and technological feedback loops. For instance, Agile principles reduced unnecessary iterations, while Six Sigma protocols helped minimise defect rates. Such integration advances the field by shifting from disconnected sustainability tactics to a structured,

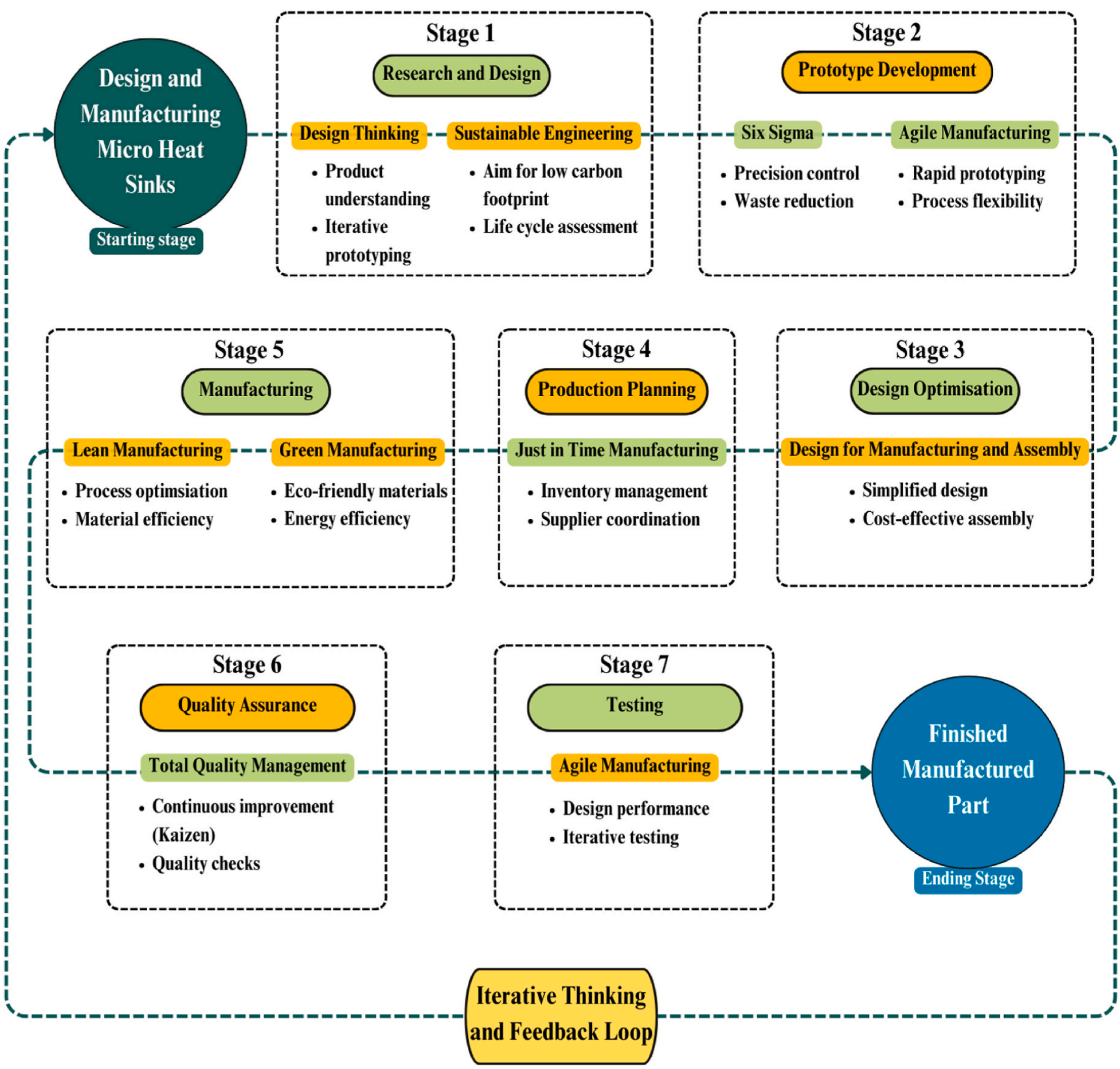

Fig. 5. Systematic hybrid intelligence framework integration.

continuous improvement methodology, reflecting a deeper systems-thinking approach often missing from current TEA or CE literature.

Thirdly, to the best of our knowledge, this is the first application of supervised machine learning models (Linear Regression and Random Forest) to validate cost estimates in a hybrid circular manufacturing context for thermal devices. The Random Forest model, with an R^2 of 0.986 and RMSE of 11,116 USD, demonstrated strong predictive alignment with actual outcomes. This not only enhances confidence in the model's predictive robustness but also opens up new pathways for using AI in lifecycle decision-making and investment risk mitigation. It represents a shift towards digitalised sustainability verification—a pressing need in the industry. Moreover, this study enriches CE theory by operationalising a multi-philosophy approach within a techno-economic-sustainability framework. It extends existing models, such as Dame Ellen MacArthur's circularity principles (Gong and Whelton, 2019), by embedding machine learning and hybrid sourcing strategies, offering a rigorous, data-driven pathway for sustainable manufacturing research.

Fourthly, we attempted to follow ISO 14006 guidelines and an integrated system design framework throughout the development process, from design ideation to prototyping and validation. Fig. 5 illustrated the systematic integration of manufacturing methodologies across the product lifecycle, supported by both primary (expert consultations, in-house experiments) and secondary (literature, databases) data. Every stage was data-informed and technologically driven. This level of intentional integration has not been previously demonstrated in thermal management manufacturing. The result is a replicable, modular system—here proposed as the Sustainable Hybrid Intelligence Framework (SHIF)—which can be adopted by SMEs or larger manufacturers. SHIF provides a practical scalable, data-driven blueprint for manufacturers to implement circular economy principles in micro heat sink production. By leveraging hybrid sourcing, machine learning, and integrated manufacturing philosophies, firms can achieve cost efficiency, reduce environmental impact, and enhance product quality, making it directly applicable to industries like electronics and thermal management.

Lastly, while prior studies explored TEA or sustainability improvements for thermal management systems or energy systems, these have generally relied on static LCA models, with little focus on adaptive/hybrid production. For example, many assessments fail to address dynamic sourcing strategies or the integration of quality philosophies. In contrast, our work introduces a modular, dynamic, and circular framework that adapts to design changes, market variability, and environmental targets simultaneously, enhancing theoretical and practical applicability.

Therefore, the implications of this work are multi-layered. Academically, it advances interdisciplinary methodologies by integrating manufacturing science, machine learning, and environmental sustainability. Industrially, it offers a scalable framework for decision-making under cost and carbon constraints, applicable to diverse stakeholders engaged in global production. From a policy perspective, it aligns closely with the UK's Net Zero Strategy, the EU Green Deal, and the UN Sustainable Development Goals, particularly SDGs 9, 12, 13, and 17 (Fund, 2015), providing a pathway for economically viable climate action. Beyond technical contributions, this study emphasizes the human and organisational dimensions of sustainable engineering. The adoption of Total Quality Management (TQM) and Lean philosophies necessitated internal training, process transparency, and a quality-first mindset. By embedding sustainability into daily operations and design decisions, offering both cultural and procedural transformation in manufacturing settings. The study's scientific depth is strengthened by its use of validated machine learning models and ISO 14006-guided eco-design, ensuring robust, reproducible results. Additionally, the integration of primary and secondary data sources, including expert consultations and lifecycle databases, grounds the SHIF in empirical evidence, addressing gaps in static LCA models and advancing data-driven circular economy research.

However, it is important to acknowledge that the study's scope was bounded by assumptions such as static energy grid mixes and limited access to real-time emissions data. In future work, the methodology could be enhanced by integrating dynamic life cycle assessment (LCA) models, blockchain-based material traceability, and real-time environmental sensors. Furthermore, expanding the machine learning models to predict not only production costs but also sustainability indices—such as embodied carbon and circularity scores—could make the framework more holistic and predictive. Nonetheless, this critical discussion articulates the core contributions of our study in advancing a techno-economically viable and environmentally responsible manufacturing model. Through a multi-philosophy, machine learning-augmented hybrid production strategy, we propose a structured yet flexible system that aligns with industry objectives, policy mandates, and academic advancement. The Sustainable Hybrid Intelligence Framework (SHIF) emerging from this research offers a new blueprint for circular and smart manufacturing.

7. Conclusion

This study proposed a Sustainable Hybrid Intelligence Framework (SHIF) for micro heat sink manufacturing by combining hybrid production strategies with lean, green, and agile design philosophies. Through a UK–China cross-case analysis, the hybrid approach—producing simpler components in-house while outsourcing complex parts—achieved significant outcomes: a 19 % reduction in carbon emissions, 29 % energy savings, and 43 % cost reduction. Lifecycle performance was enhanced through material recycling and sustainable end-of-life design, while iterative prototyping and additive manufacturing improved thermal performance. Machine learning models validated the cost-saving predictions with high accuracy ($R^2 = 0.98$). This framework aligns with global sustainability targets, particularly UN SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals).

Implications for Theory: SHIF enriches circular economy theory by demonstrating how hybrid intelligence integrates lean, green, and agile principles to optimise resource use and minimise waste in micro heat sink production. It advances techno-economic-sustainability models by embedding machine learning for precise cost and environmental impact predictions, offering a novel lens for studying closed-loop manufacturing systems.

Implications for Practice: SHIF provides manufacturers with a practical roadmap for circular economy adoption in micro heat sink development. By combining in-house production, outsourced components, and strategic manufacturing, firms can achieve cost and energy efficiency while prioritising reusable components and materials. This approach supports data-driven decisions, enabling industries to meet sustainability targets without compromising performance.

Implications for Society: SHIF promotes societal benefits by reducing emissions and fostering resource-efficient production, aligning with global sustainability goals. The UK–China collaboration model encourages cross-border innovation, enhancing access to sustainable technologies and supporting equitable industrial progress in line with circular economy principles.

While SHIF offers significant benefits, its adoption in resource-constrained settings may require tailored strategies to overcome initial training barriers. Future research should focus on scalability in high-volume production, integrating bio-based materials, and developing automated systems to reinforce circular economy integration. Overall, the study offers a robust baseline for advancing manufacturing and addressing economic, operational, and environmental challenges.

CRediT authorship contribution statement

Mohammad Harris: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hongwei Wu:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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