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A Project-based Approach to Sustainability awareness in Product Design and Processes for Manufacturing Education

Dr. Muyue Han, North Carolina A&T State University

Dr. Muyue Han is an Assistant Professor in the Department of Industrial and Systems Engineering at North Carolina A&T State University. Her research focuses on advancing the theories and applications of sustainable and smart manufacturing. She is also engaged in integrating sustainability principles into engineering education through experiential and analytics-supported learning approaches.

Joao Paulo Jacomini Prioli, North Carolina Agricultural and Technical State University

Dr. Joao Prioli is an Assistant Professor at North Carolina A&T State University. He received his Ph.D. and M.S. in Industrial and Systems Engineering from Wayne State University and holds a B.S. in Electrical Engineering from the University of Uberlândia. His research focuses on advancing automation solutions to support the circular economy, with a particular emphasis on smart manufacturing, CAD-based disassembly, and human-robot collaboration. His work explores data-driven modeling and automated disassembly processes to enable sustainable production and resource recovery.

Dr. Steven X. Jiang, North Carolina A&T State University

Dr. Steven Jiang is an Associate Professor in the Department of Industrial and Systems Engineering at North Carolina A&T State University. His research interests include Human Systems Integration, Visual Analytics, and Engineering Education.

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Abstract

Modern manufacturing relies on automated systems like CNC machining for its precision, adaptability, and efficiency. However, this focus on operational performance often overlooks critical environmental impacts across a product's entire life cycle. As a result, environmental considerations, from design and processing to end-of-life, remain inconsistent and context-dependent. The increasing attention to energy consumption, emissions, and material circularity makes it imperative to integrate sustainability thinking into manufacturing education. To address this gap, this study introduces an instructional module designed to incorporate sustainability-informed product design and processing concepts into a manufacturing processes course. Guided by the Engineering for One Planet framework, the module emphasizes systems thinking, material selection, and design-for-environment strategies. A project-based learning activity is developed in which students redesign a clock base and program CNC G-code to explore environmentally conscious design alternatives and resource-efficient toolpath planning. A component to this module is the use of Large Language Models (e.g., ChatGPT) as creative co-design tools, which allows students to brainstorm new design options and reflect on how digital assistance influences their decision-making. Student learning was assessed using pre- and post-course self-reported surveys and qualitative word cloud analyses. Student project outcomes were further analyzed using a cross-impact mapping matrix to identify relationships among life cycle sustainability and different design and processing strategies. Results indicate that integrating sustainability frameworks within hands-on manufacturing and design activities, supported by generative AI tools, enhances students' ability to connect design and process planning intents with life cycle considerations and fosters systems thinking for tackling sustainability challenges.

Keywords: Sustainability integration, project-based learning, design and manufacturing, Engineering for One Planet.

1. Introduction

Manufacturing plays a central role in the U.S. economy and in shaping national energy use, material consumption, and environmental outcomes. In recent years, the manufacturing sector has contributed approximately $2.3 trillion to gross domestic product and supported more than 15 million jobs, indicating its economic significance [1]. Beyond these economic metrics, manufacturing activities strongly influence energy demand, resource utilization, waste generation, and emissions across product life cycles. As global challenges such as energy insecurity, competition for critical resources, and supply chain disruptions intensify, manufacturing organizations face increasing pressure to maintain economic competitiveness while simultaneously advancing sustainability goals [2], [3]. Recent manufacturing-related national initiatives and strategic research investments reflect this dual focus by emphasizing domestic manufacturing revitalization alongside improved resource efficiency, long-term sustainability, and system resilience [4], [5], [6].

These shifts have heightened expectations for the manufacturing workforce. Modern manufacturing increasingly relies on automation and digital tools, such as CNC machining and computer-aided manufacturing (CAM), to deliver precision, repeatability, and productivity. At the same time, engineers are expected to incorporate sustainability considerations into manufacturing decisions not as optional add-ons, but as core professional competencies [7]. Decisions related to material selection, tooling strategies, machining parameters, and production planning now have implications that extend well beyond the factory floor and influence environmental impacts across the product life cycle. Preparing future industrial and manufacturing engineers to navigate these interconnected challenges requires educational approaches that move beyond isolated process control, and instead emphasize systems thinking and sustainability-informed decision making [8].

From an educational perspective, this need places particular importance on engineering courses such as industrial production and manufacturing processes, which often serve as a core component in industrial and systems engineering curricula. These courses introduce students to how design intent is translated into manufacturing operations through activities such as material and tool selection and machine programming. Traditional instruction in manufacturing processes has focused on operational performance metrics, such as manufacturability, dimensional accuracy, surface finish, and productivity. However, the growing prominence of sustainability metrics in industrial practice, including energy consumption, material circularity, and techno-economic performance, increasingly requires students to effectively "reverse engineer" manufacturing decisions from a life-cycle perspective.

To address this educational need, this paper presents the development and implementation of a sustainability-integrated manufacturing processes module guided by the Engineering for One Planet (EOP) framework. Sustainability concepts were progressively integrated into the existing course contents through targeted in-class discussions, peer-led presentations, and guided after-class readings. In addition, sustainability considerations were explicitly incorporated into and assessed through a project-based learning (PBL) activity focused on the redesign and CNC process programming of a clock base. Through this project, students were encouraged to consider sustainability-oriented re-design and processing strategies across multiple life-cycle stages, while engaging in standard manufacturing process planning and machine programming tasks. For the representative course selected, this study discusses the alignment between EOP framework student learning outcomes and course Student Learning Objectives (SLOs), provides example instructional modifications made to course content and project design, and the assessment approaches of student learning.

2. Background and Motivations

2.1 Sustainability Integration in Manufacturing Education

A growing body of engineering education research has explored methods for incorporating sustainability into undergraduate engineering curricula. Early studies emphasized sustainability awareness and competency development across engineering programs, highlighting the importance of life-cycle thinking and environmental responsibility in engineering practice [9], [10], [11]. In engineering education, common approaches include the use of life-cycle assessment (LCA) tools to quantify environmental impacts [12], [13], the introduction of sustainability indicators to support material and process selection , and the use of case studies to illustrate trade-offs among economic, environmental, and technical objectives [14], [15]. These efforts have been shown to improve student awareness of sustainability issues and enhance their ability to discuss environmental impacts in engineering contexts.

Within manufacturing education, sustainability has often been introduced through supplementary modules or post hoc evaluation. For example, students may complete an LCA exercise after a part has been designed and manufactured or evaluate sustainability metrics as part of a reflective report [16], [17]. While such approaches are valuable for raising awareness, prior research has demonstrated that manufacturing process planning decisions can significantly influence energy consumption, material efficiency, and overall environmental impact [18], [19], [20]. In comparison, PBL activities in manufacturing courses typically emphasizes feasibility, manufacturability, and part quality [21], [22]. Such activities can inadvertently reinforce a "quality-first" mindset, which leads students to prioritize traditional performance metrics while overlooking sustainability metrics. As a result, students may struggle to connect sustainability concepts with the practical manufacturing variables they directly control.

2.2 EOP Framework in Engineering Education

The EOP framework was developed to support the systematic integration of sustainability into engineering education. The framework emphasizes systems thinking, material selection, design-for-environment strategies, and explicit consideration of life-cycle impacts in engineering decision making. Rather than prescribing specific course content, EOP offers a flexible structure for embedding sustainability across disciplines and course types, supported by instructor-facing implementation resources and teaching activity guides [23]. Published implementations of EOP have been reported in multiple curricular contexts. Several studies document EOP-driven integration in design-focused courses and design curricula [24], [25], where sustainability principles and EOP outcomes are embedded into project requirements and student deliverables. Additional implementations have been reported in civil engineering programs, including EOP mini-grant efforts that emphasize sustainability literacy and structured curriculum enhancement

[26], [27]. Studies also suggest that EOP competencies and outcomes can be studied within PBL settings, including student recognition and use of EOP-aligned competencies in PBL experiences [28], [29]. Further, EOP has been used to inform modules in selected core engineering science courses, such as structural steel design and thermodynamics [30], [31], which demonstrates its applicability in extending discipline-specific studies to different fields in engineering.

2.3 Motivation for an EOP-guided Module for Manufacturing

While prior work has established the importance of sustainability in engineering education and demonstrated the value of EOP frameworks, relatively few studies have applied the EOP framework within hands-on manufacturing processes courses, particularly those centered on digital manufacturing workflows such as CNC machining, CAM-based process planning, and G-code programming. Manufacturing processes courses offer a particularly impactful setting for this integration because they sit at the intersection of design intent and production execution. Unlike purely analytical or conceptual courses, manufacturing processes courses require students to make concrete decisions. In this context, this propagation is tangible and observable: small changes in part design or toolpath strategy can alter material removal rates, machining time, energy demand, and waste generation. Integrating sustainability considerations at these decision points enables students to experience sustainability not as an abstract principle or retrospective evaluation, but as an integral dimension of everyday manufacturing decision making.

3. Design and Implementation of Sustainability-integrated Learning Module

3.1 Course Description and Applied Pedagogy

In this project, the learning module was developed and implemented within the course: Industrial Production Processes, a required junior-year undergraduate course in the Industrial and Systems Engineering (ISE) curriculum. The course introduces a broad range of manufacturing processes, including casting, forming, material removal, joining, and assembly, with accompanying laboratory activities focused on both manual and CNC machining. Core learning objectives emphasize the working principles of basic manufacturing processes, process planning and operations, tooling and fixture design, procedures for measurement and quality assurance, and the apply knowledge and skills in real life manufacturing problems that ensure a smooth translation from design intent into executable manufacturing. The lecture sessions are complemented with a series of laboratory sessions for hand-on assignments and course projects, including equipment such as injection molding, 3D printers, and CNC machining. Prior to the curriculum modification, course project is design for fabricating a tabletop clock, which consists of both plastic and metal components, where students conduct process planning, programming, and final assembly as teams.

3.2 Course-level Design for Sustainability Integration using EOP Framework

Prior to the curriculum modification, sustainability-related topics were addressed implicitly through discussions of materials and manufacturing processes but were not systematically embedded as explicit student learning outcomes or assessment criteria. A central element of the module development was the intentional alignment between course SLOs and EOP student learning outcomes. The EOP framework was used to guide the redesign of instructional modules and project activities by explicitly mapping selected course SLOs to relevant EOP outcomes, as summarized in Table 1. This SLO-EOP mapping served as a course redesign tool to identify where sustainability considerations could be embedded directly into existing manufacturing topics, ensuring coherence between instructional content, project requirements, and sustainability learning outcomes. The resulting course module and project modifications were designed to support ABET Criterion 3 student outcomes 1 and 2, which emphasize the ability to identify, formulate, and solve complex engineering problems and to apply engineering design to produce solutions that meet specified needs while considering public health, safety, welfare, and global, cultural, social, environmental, and economic factors.

Table 1. Alignment of course SLOs to EOP framework student learning outcomes

Selected SLOs	EOP Framework	Description
– Describe basic mfg. processes including material removal, casting, forming, & joining. – Recognize other processes & techniques related to manufacturing. – Apply knowledge and skills in real life manufacturing problems.	System Thinking	Is able to consider and understand tradeoffs and identifies impacts during process selection in product lifecycle (i.e., environmental, economic and social considerations).
– Plan appropriate steps to produce simple parts using typical machines such as lathe, milling, injection molding, etc. – Describe planning theory and transformation processes used in discrete parts production.	Materials Selection	Identify potential impacts of material selection in different manufacturing processes during and post production.
– Design and develop process plans, jigs, fixtures and gages. – Develop procedures for measurement, inspection, and quality assurance.	Design	Is able to design for the environment and society based skills (e.g., design for repairability and durability, design for disassembly, flexibility, and reuse).

3.3 Integration of Sustainability into Course Modules

Following the EOP-guided alignment of course learning objectives, sustainability considerations were embedded into existing course modules by extending traditional manufacturing topics with sustainability-oriented perspectives. Rather than introducing separate sustainability lectures, EOP-aligned concepts were integrated within instruction on material properties, manufacturing process selection, machining, and design for manufacturing and assembly. Instructional activities were designed to help students understand that manufacturing sustainability is driven by a chain of precursive and successive decisions. Lectures provided specific examples of how energy consumption and greenhouse gas (GHG) emissions are influenced by upstream logistics and raw material extraction, as well as how downstream customer mindsets regarding product selection impact a product's environmental footprint. To address the "successive" phase, students explored design mechanisms that facilitate re-x (e.g., remanufacturing, reuse, and recycling) processes. To support data-driven decision-making, students were introduced to federal energy and GHG emission databases (e.g., US EPA eGRID), providing them with empirical benchmarks for their projects. Furthermore, the module highlighted large-scale industry initiatives, such as Amazon's commitment to achieving net-zero carbon, to illustrate the economic and corporate drivers behind sustainable manufacturing.

These sustainability considerations were embedded in course project that was developed with a focus on the redesign and CNC manufacturing of a clock base. The project required students to modify a provided clock base design using CAD software and to generate validated CNC G-code for milling the redesigned part. This project reinforced the core manufacturing competencies such as tooling selection, process planning, and simulation-based verification along with material selection and decision impact. Through this activity, students engaged in the full digital manufacturing workflow, including design ideation, CAD modification, CAM toolpath generation, CNC G-code development, and simulation, while explicitly considering sustainability-related trade-offs embedded within each decision, as illustrated in **Error! Reference source not found.**.

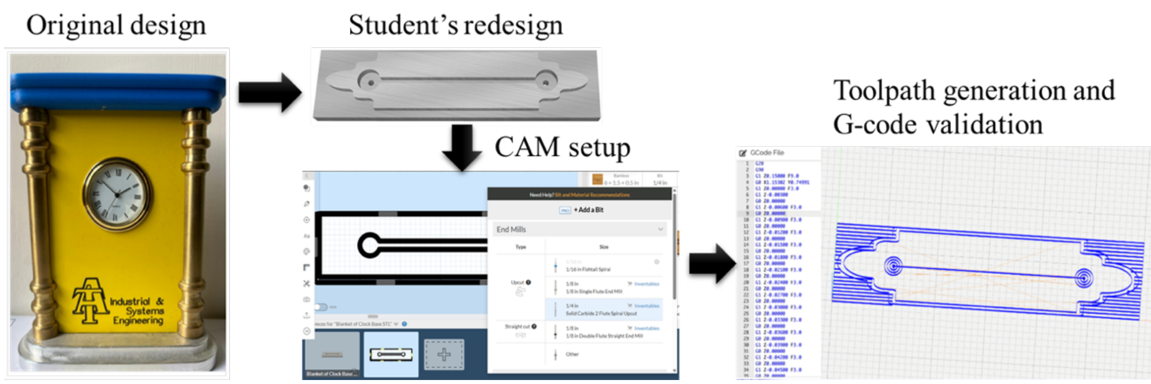

Figure 1. Illustrations of clock assembly design and project workflow

Consistent with the project description, students were asked to:

- Redesign the clock base using CAD-based software (e.g., OnShape, SolidWorks), modifying geometry while maintaining functional requirements.
- Select cutting tools and machining strategies and justify these choices based on manufacturability and efficiency.
- Generate and verify CNC G-code using CAM software to ensure safe and correct execution prior to machining given the material chosen.
- Analyze sustainability implications of their design and process choices, including energy use, material waste, and tool life.
- Examine the relationship between machining time and energy consumption, and propose at least one strategy to reduce cycle time and associated energy use (e.g., toolpath optimization).
- Reflect on material use and end-of-life considerations, including recyclability, waste generation (e.g., chips/swarf), and potential reuse or disposal pathways.

4. Assessment and Data collection

In this study, a mixed-methods assessment approach was adopted. Data were collected through pre-post student surveys and systematic analysis of student project deliverables. This study was conducted with approval from the Institutional Review Board (IRB, HS24-0096, "*NLI:*

Research: Integrating Sustainability into Industrial and Systems Engineering Curriculum"), and all data were collected in accordance with approved human subjects research protocols.

Surveys were designed to capture students' understanding and perceptions of sustainability and sustainable manufacturing concepts using a combination of descriptive, open-ended questions and Likert-scale items. The surveys were administered at two points: at the beginning of the semester, prior to explicit sustainability instruction, and at the end of the semester, following completion of project-based learning activities. This pre-post design enabled examination of changes in student perceptions and conceptual understanding over the duration of the course. In parallel, student project outcomes from the clock base redesign activity were analyzed to assess how sustainability considerations were reflected in design and manufacturing decisions. A cross-impact mapping approach was used to examine the relationships between proposed sustainability actions and life-cycle stages, enabling identification of which stages received the greatest attention across student projects.

5. Results and Discussions

5.1 Student Sustainability Perceptions

For Part I of the student survey, which consisted of two open-ended questions: in Q1, students were asked to provide words describing sustainability, while in Q2, students identified sustainability-related issues. Separate word clouds were generated for the pre- and post-surveys (Figure 2), with word size representing the frequency of occurrence across responses.

The pre-survey word clouds for both questions indicate that students entered the course with a baseline awareness of sustainability; however, this awareness was mainly expressed through broad, high-level concepts and global environmental challenges. In Q1, students commonly described sustainability using abstract descriptors such as "*renewable, balanced, efficient, and responsibility*." Similarly, Q2 responses emphasized large-scale issues such as "*pollution, climate change, deforestation, and waste*." These results suggest that, prior to instruction, students primarily viewed sustainability as a general environmental concern. In comparison, the post-survey word clouds reflect a shift toward more specific, applied, and engineering-relevant language. In post-survey Q1 (Figure 2b), there are more diverse descriptions of sustainability using terms such as "*eco-friendly, recycling, and resilient*," where abstract definitions were increasingly clustered with interpretations related to engineering practice. In Q2, while global concerns remained present, students more frequently stated actionable sustainability challenges such as "*energy, carbon emissions, consumption, efficiency."*

When reviewed together, the Q1 and Q2 results suggest that students began to conceptualize sustainability not only as an environmental issue, but also as a set of challenges that can be addressed through engineering decisions related to resource management, efficiency improvement, and end-of-life considerations. Compared with the pre-survey results, the post-survey responses show improved alignment between how students defined sustainability (Q1) and the issues they identified (Q2). Rather than viewing sustainability as a standalone or abstract concern, students increasingly framed it as an integral component of production, management, and actionable decision making.

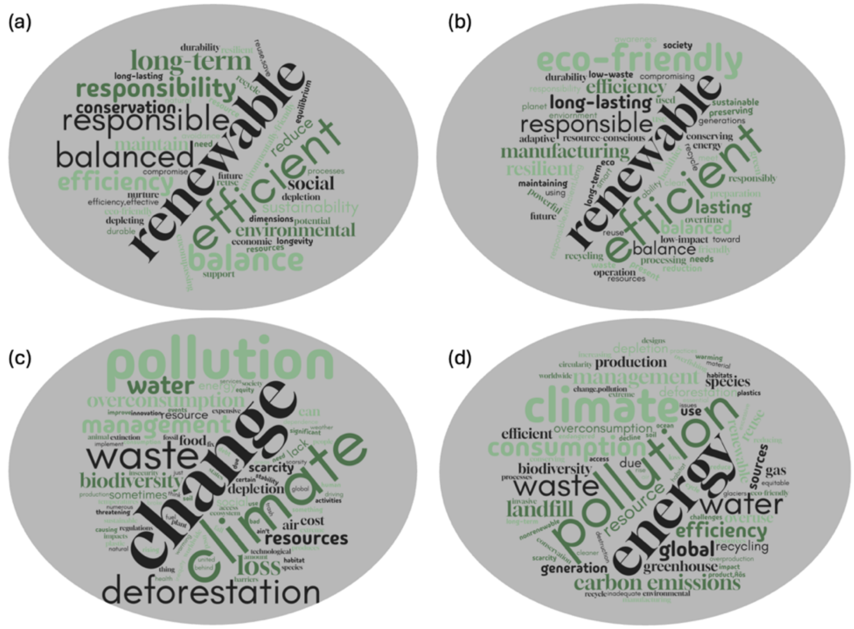

Figure 2. Word clouds of students' perception on sustainability: (a)-(b) Q1, and (c)-(d) Q2.

5.2 Surveys on Sustainability in Manufacturing

The pre- and post-course surveys included Likert-scale items designed to quantify shifts in student familiarity and confidence regarding sustainability in manufacturing. Students rated their agreement with statements on a five-point scale (1 = Strongly disagree/very familiar to 5 = Strongly agree/not familiar at all). As summarized in the Table 2, the results suggest a positive instructional impact on student's awareness and willingness to integrate sustainability into engineering decision-making. Despite these overall gains, some items, particularly those related to the frequency of considering environmental impacts in daily life and the willingness to prioritize sustainability when faced with increased cost or complexity, remain below a mean rating of 4. This finding suggests that, while students' conceptual understanding and attitudes toward sustainability improved, applying sustainability principles in habitual behaviors and cost-sensitive design decisions remains challenging. Addressing this gap may require additional instructional emphasis on complex, real-world decision-making, as well as both horizontal and vertical integration of sustainability concepts across the curriculum. In particular, expanding sustainability discussions beyond manufacturing-focused courses to include courses such as Engineering Project Management, Engineering Economics and Cost Analysis may help support deeper integration of sustainability into professional practice.

Table 2. Pre- and post-course mean responses to Likert-scale survey questions

Likert-scale Questions	Pre-survey	Post-survey
1. How often do you consider the environmental impact of your energy and resource usage in daily life?	3.5	3.6
2. As a future engineer, how willing are you to prioritize sustainable resource use (e.g., energy efficiency, waste reduction) in your designs and projects, even if it increases costs or complexity?	3.5	3.7

3. How strongly do you agree with the statement: “Engineers have a professional responsibility to prioritize pollution reduction in manufacturing processes.”	4.2	4.4
4. How familiar are you with sustainable manufacturing practices aimed at reducing harmful pollutants (e.g., emissions, chemical waste, microplastics)?	4.3	4.6

Beyond the Likert-scale items, students also responded to two multiple-selection questions examining their understanding of technical sustainability concepts: “(i) *Which of the following are direct sustainability benefits that can result from product design and optimized process control? (select all that apply)”* and “(ii) *Which Circular Economy practices are most critical for sustainable manufacturing? (select up to 3).”* Comparisons between pre- and post-survey responses to these questions are shown in **Error! Reference source not found.**.

Error! Reference source not found.(a) illustrates changes in students’ perceptions of the direct sustainability benefits associated with product design and optimized process control. Post-course responses show a substantial increase in consensus regarding energy efficiency and reduced production costs, with all respondents identifying this benefit in the post survey, compared to 83.3% in the pre survey. Recognition of material efficiency remains high (>83%), though slightly reduced, likely reflecting more selective attribution of benefits that are directly controlled through engineering design and process optimization. Perceived benefits related to labeling and branding, product affordability, and long-term competitiveness show smaller changes. These trends highlight opportunities to further strengthen the integration of economic sustainability considerations, either through enhanced instructional materials or coordination with complementary courses.

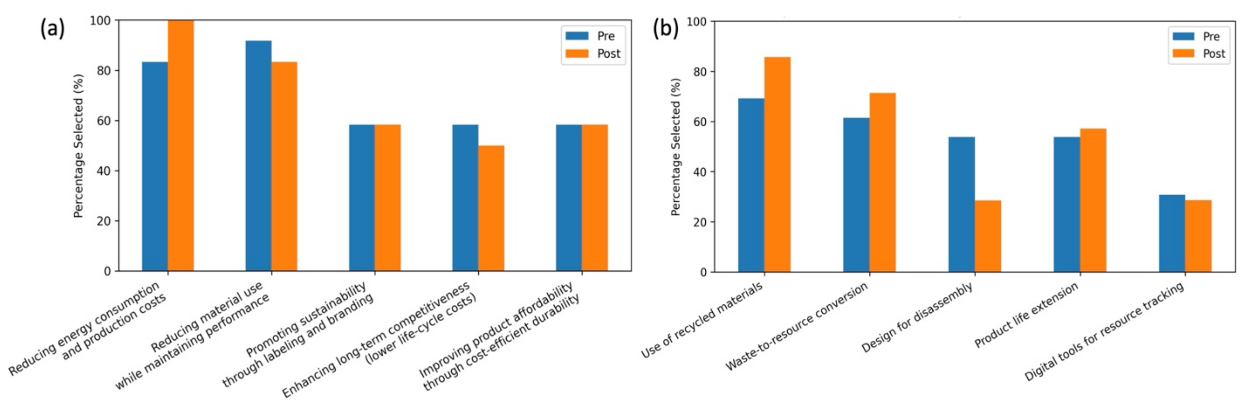

Figure 3. Pre-post comparisons of (a) perceived direct sustainability benefits from product design and process optimization and (b) circular economy prioritization for sustainable manufacturing.

Figure 3(b) presents changes in students’ prioritization of Circular Economy (CE) practices for sustainable manufacturing. Post-survey results indicate increased attention on use of recycled or renewable materials (selection increased from 69.2% to 85.7%) and waste-to-resource conversion (increased from 61.5% to 71.4%), which suggest improved understanding of material circularity and closed-loop resource flows. Small increase in product life extension suggests growing awareness of design decisions that influence product life-cycle performance. In comparison, prioritization of design for disassembly/remanufacturing declined in the post survey.

This trend is likely influenced by course structure and project scope: with students limited to selecting their top three practices, many prioritized strategies they had more direct exposure to and hands-on experience with in their course projects (see Section 5.4). This interpretation is supported by the distribution of redesign strategies observed in students' project outcomes, which indicate a more nuanced and experience-driven prioritization of CE practices.

5.3 Analysis of Digital Assistance and Creative Co-design

A key component of this module was the use of Large Language Models (LLMs) as creative co-design tools. These tools allowed students to brainstorm diverse design options and reflect on how digital assistance influenced their engineering decision-making. By acting as a "conceptual partner," the LLM helped students bridge the gap between abstract sustainability goals and the technical constraints of CNC machining. To facilitate this, students were encouraged to use structured prompts to explore the relationship between design intent and life cycle impacts. Examples of prompts used by students included:

- Role-based Brainstorming: "*Act as a sustainable manufacturing engineer. Suggest three geometric modifications to a rectangular clock base that would reduce material waste during CNC milling without compromising structural stability.*"
- Constraint-driven Analysis: "*I am switching my clock base material from 6061 Aluminum to a bio-composite. How should I adjust my spindle speed and feed rate to minimize energy consumption while maintaining a high-quality surface finish?*"
- Trade-off Evaluation: "*Compare the life cycle impact of a clock base designed for 'infinite' durability versus one designed for easy disassembly and material recycling. Which approach is more sustainable for a small consumer electronic product?*"

Student reflections indicated that while the LLM provided a wide range of creative alternatives, the students' primary role shifted from purely generating to evaluating. They had to critically assess AI-generated suggestions against real-world manufacturing variables like tooling availability and G-code validation. This interactive process fostered the systems thinking necessary to tackle complex sustainability challenges, ensuring that digital assistance enhanced, rather than replaced, the engineering design process.

5.4 Student Project Outcomes

To examine patterns in how students associated sustainability-oriented redesign strategies with different product life-cycle stages, student project reports were reviewed and qualitatively coded and subsequently visualized using a frequency-based heat map. An initial set of redesign strategy categories was informed by course learning objectives and project prompts and then refined inductively through iterative review of student reports to identify recurring sustainability-related design intents articulated by students. Conceptually similar ideas were consolidated into higher-level strategy categories to improve interpretability in the visualization. Each student project was coded using binary indicators to capture whether a specific sustainability strategy was explicitly proposed or discussed in relation to a given life-cycle stage. The aggregated coding results were used to construct a life cycle stage-redesign strategy matrix, as shown in Figure 4, where cell values represent the frequency of co-occurrence across the cohort (n = 24 student reports).

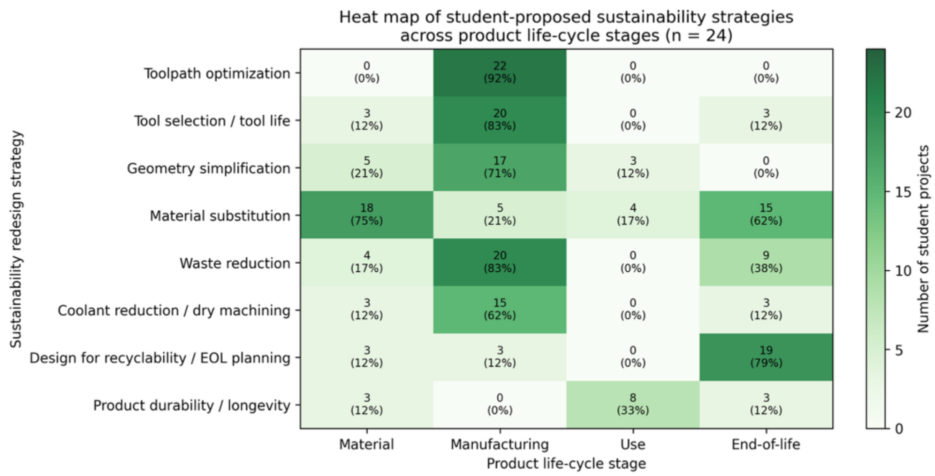

Figure 4. Heat map of sustainability-aware redesign strategies across product life-cycle stages

As reflected in the heat map, students most frequently associated sustainability considerations with the manufacturing and processing stage, followed by clusters related to material selection and end-of-life stages. At the process level, students' redesign ideas indicate a strong emphasis on connecting sustainability to manufacturing decisions, with commonly reported strategies focused on tool selection, toolpath optimization, and waste reduction. For example, students proposed toolpath modifications to reduce machining time and associated energy use, the selection of tools compatible with the workpiece material to minimize tool wear, and reductions in unnecessary material removal to decrease chip waste. In terms of material selection and end-of-life stages, students frequently proposed material substitution strategies, most often comparing aluminum and steel in terms of machinability, energy intensity, cost, and recyclability.

Discussions on the high recyclability of aluminum and value of clean chip recovery from CNC machining were also reported, while others explored alternative materials such as bio-degradable materials (e.g., wood and bamboo) to reduce embodied energy and/or improve end-of-life disposal options. Redesign strategies associated with end-of-life were centered around recyclability, reuse, which indicates students' engagement with CE concepts. It is worth noting that redesign strategies reflected limited attention to use-stage sustainability relative to other life-cycle stages. When observed, students most often referenced durability, longevity, and ease of assembly. Examples include adding chamfers to facilitate smoother clock insertion during assembly, softening internal corners to support cleaner toolpaths and reduce stress concentrations, and adding recessed features to prevent chipping during use. While these redesigns indicate some awareness of use-phase performance, they were less emphasized than manufacturing efficiency/recyclability. This pattern is consistent with the operation-focused nature of the course and suggests opportunities for future instructional module improvement, including the integration of topics such as maintenance and functional degradation.

6. Conclusions

This study demonstrates that a project-based learning approach guided by the EOP framework effectively integrates sustainability into core manufacturing education by shifting student focus from isolated process control to holistic systems thinking. By embedding sustainability-informed decisions directly into digital manufacturing workflows, such as CNC G-code programming, toolpath optimization, and material selection, students successfully transitioned from viewing sustainability as an abstract environmental principle to treating it as a core professional competency. The inclusion of LLMs as creative co-design tools further enhanced this process, allowing students to brainstorm diverse design alternatives and evaluate life cycle trade-offs through an iterative "evaluate-and-validate" cycle that bridged conceptual design with applied manufacturing practices. While the module successfully improved students' ability to link design intent with manufacturing efficiency and material circularity, the results also identified the need for continued instructional focus on extended dimensions of sustainability, including economic sustainability and life-cycle engineering, to support more comprehensive sustainability-integrated engineering education. Ultimately, this framework provides a practical and transferable model for preparing the future manufacturing workforce to balance high-precision technical productivity with long-term environmental responsibilities.

Acknowledgement

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