Some Interventions for Sustainability Leveraged Mechanical Engineering Education

Kapil Gupta[1], Shailendra Pawanr[2*], Mfundo Nkosi[3]
University of Johannesburg, Doornfontein Campus, Johannesburg 2028, South Africa
shailendrap@uj.ac.za

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Abstract: Embedding Sustainable Development Goals (SDGs) into engineering education is critical to prepare engineers who are both technically skilled and socially responsible. Universities and nations are increasingly evaluated by their contributions toward SDGs, making sustainability a central element of modern curricula. Integrating sustainability not only fosters economic growth, environmental protection, and social impact but also encourages learners to balance technical excellence with societal welfare. Quality education, as emphasized in SDG 4, is achieved when engineering programs move beyond technical training to encourage values of responsibility, ethics, and sustainability in future engineers. Sustainability-integrated engineering curricula require awareness, knowledge-building, involvement, and collaboration attempts. This article covers some important aspects of embedding sustainability in engineering education. With the help of showcasing some interventions and work carried out on sustainability-integrated teaching, learning, and projects, conducted at one of the leading international Pan African universities, this article aims to disseminate the concept of sustainable engineering education and encourages future interventions to establish the field further.

Keyword: Curriculum Reform, Engineering Education, SDG, Teaching and Learning

Introduction

In the present time, integrating sustainability into engineering education is key to addressing global social, economic, and environmental challenges. This involves educating learners, training lecturers, and engaging stakeholders, as engineers play a central role in designing sustainable systems and technologies. Embedding sustainability interventions can transform engineering education, equipping future engineers with the skills and values to apply sustainability in practice (Ramirez-Mendoza et al., 2020). Today, industries and institutions worldwide adopt sustainability principles—whether to comply with regulations, act responsibly, or remain competitive. As per the survey conducted by a group of researchers from a Latin American institution, most of the institutes and universities were deeply rooted in environmental education and students had a limited awareness about education for sustainable development (Acosta-Castellanos et al., 2024).

The surveyors suggested incorporating transition strategies and unique ways to integrate SDGs into engineering education. Sustainable engineering education represents a paradigm shift from traditional curricula that prioritize technical proficiency to one that emphasizes a holistic approach, integrating environmental, social, and economic dimensions to strengthen sustainability

(Gutierrez-Bucheli et al., 2022). This educational model seeks to produce engineers capable of addressing problems and designing solutions that align with the United Nations' Sustainable Development Goals (SDGs), particularly in areas such as affordable clean energy, sustainable cities, industry and infrastructure, responsible consumption, and climate action(Fredriksson & Dwek, 2021). To achieve this, engineering programs must incorporate collaborative and interdisciplinary approaches, including sustainability-based curricula with SDG-aligned course contents, carrying out projects and problems, and conducting training, to address complex sustainability challenges effectively. Additionally, experiential learning methods, including project-based learning, industry collaborations, and community engagement, are critical in providing students with practical exposure to real-world sustainability challenges (García-Aranda et al., 2023).

However, achieving sustainable engineering education comes with its challenges. Resistance to change, the need for faculty training, and the alignment of curricula with industry demands are some of the hurdles that educational institutions must overcome. The possible strategies to overcome such barriers can be adopted by aligning the institution's strategic goals and plans with SDGs. Through academic excellence, innovative research and education, and community engagement, societal im-pact and environmental protection should be pursued. Interdisciplinary engagements and training to incorporate sustainability interventions are solicited. Collaborations between academia, industry, and governments are essential to developing accreditation standards, funding resources, and frameworks that support sustainability-focused programs. It is also mandatory to ensure that learners and trainers remain ethically responsible in this transformation and journey to achieve excellence and sustainability. It is also imperative that all the stakeholders should be made aware of the policies and regulations in place for sustainability. Constituting students' societies and chapters and their engagement with communities to solve local and global sustainability problems can play a vital role. Strategies for sustainability mapping evaluation and record-keeping should also be in place. Figure 1 presents some important aspects of sustainable engineering education.

Besides theoretical learning to gain knowledge, its use to solve real-world problems by applying critical thinking ability, experiential learning in the form of laboratory experiments and tests, projects and case studies, and problem-solving tasks, is essential. Sustainable engineering education directly contributes to SDG 4 quality education. It is grounded on strengthening economy, society, and environment, and supporting people, planet, and profit. SDG 17 partnership for the goals is believed to be a key, not only to promote sustainable and quality education but also to pursue other SDGs.

There are some past attempts at integrating sustainability with engineering education. In an important study, the integration of sustainability-related topics into master's programs of mechanical engineering in three top-ranked European universities has been evaluated (Hąbek et al., 2024). It was reported that despite sincere attempts, still not all students have been exposed to sustainability-related content and further scope exists to focus on societal and economic dimensions of sustainability. An important study carried out by Pujol and Tomas (Pujol & Tomás, 2020) highlights the status of robotic engineering degree students for taking action toward sustainability-related tasks. The students were given the task of designing environmentally benign robots and a survey was conducted among them to know their views on sustainability interventions. Most of the students agreed on the importance of sustainability and its inclusion in their studies. Tisdale and Bielefeldt (Tisdale & Bielefeldt, 2024) studied sustainability integration levels in engineering thermo-dynamics courses. They found that society, economy, and environment-related contents were added in such courses, and SDG 7 affordable and clean energy and SDG 12 responsible production and consumption were mainly targeted. An artificial intelligence-based sustainable engineering education tool was successfully developed for personalized teaching and effective interaction (Isaza Domínguez et al., 2024). The tool interface was de-signed in such a way that it was able to fulfil the specific requirements of any individual learner and prepare him/her for effective performance in exams and assignments. It was proved that the tool is capable of meeting various SDGs like quality education, decent work and economic growth, reduced inequalities, and responsible production and consumption. Throughout the world, SDG-based curriculum is being designed and implemented. Various studies are being conducted to evaluate the extent of such interventions followed by recommending frameworks and training. One such attempt was made by a group of researchers to boost sustainable development in civil engineering education (Gómez-Martín et al., 2021). They analysed that in their university, 75% of courses incorporated all 17 SDGs. To further boost up, it was recommended that all modules should explicitly refer to the alignment with the SDG and the students in their project reports should reflect on the contribution of their work towards the SDGs. In an important article, roles of informal and formal governance activities i.e. re-search, conferences, training, consultations, accords, policies, etc., have also been identified as important for sustainable engineering education and achieving SDGs (Chen et al., 2022).

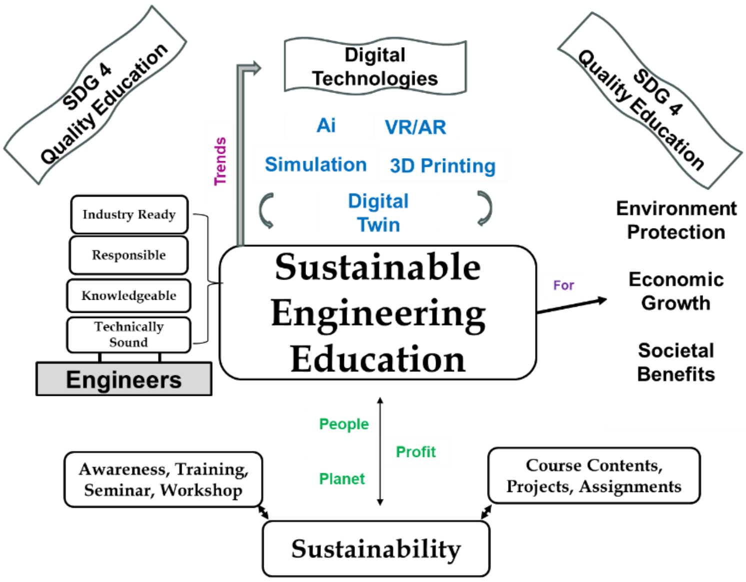


Fig. 1 - Important aspects of sustainable engineering education

In a European institution, SDGs- 6, 7, 12, and 13 were integrated into process design and engineering by introducing societal and environmental aspects (Barrio et al., 2024). The students incorporated energy consumption and environmental emissions type factors to evaluate the performance of their designed processes. After this activity, feedback from the students involved was collected. It was found that the student percentage of limited knowledge of sustainability dropped from 45 to 7%. Embedding sustainability-themed projects in engineering design was found effective in increasing sustainability-related knowledge of the students and ensured strong engagement and improvement in their abilities (Fishlock et al., 2023). In an important work, a challenge-based learning strategy was adopted, in which the postgraduate level learners learned to solve environmental issues and measure societal impact, etc. by generating sustainable solutions for various problems with a target to achieve SDG 11 (Gudonienė et al., 2021).

Considering the discussion of past work, it can be said that integration of SDGs with curriculum is being done worldwide. However considering the number of educational institutes, such attempts are seemingly scarce. The problem situation in education sector across the globe can be explained by the fact that still, a significant number of learners and lecturers are unaware of sustainability concepts and possible interventions that can contribute to shaping a better world.

They are highly unaware of the possible recognition of the efforts they are busy making in teaching, learning, and research activities. They also require some awareness and learning about relating their tasks and activities with SDGs and their proper reporting and documentation.

This article discusses some of the important ways through which sustainable engineering education has been promoted and supported, at our university, to make contributions to the UN's SDGs. The attempts corresponded to the university's strategic plan 2035 which is built on societal impact and sustainability, as one of the three pillars. The consistency and quality of such attempts have positioned our university at 46th globally for its overarching impact on pursuing sustainable development, as per the latest Times impact ranking (Times Higher Education, 2025).

The main aim of the article is to disseminate the concept of sustainability and pro-mote sustainable engineering education. It further intends to provide knowledge and develop a sound understanding of the readers about sustainability and sustainable engineering education, while encouraging the academic community to align teaching, learning, and research activities with the UN's SDGs, for societal benefits, economic growth, and environment protection. Curriculum reform with introduction of sustain-ability-related content, sustainability-based projects, and harnessing the potential of generative AI for teaching, research, and publication, for sustainability-leveraged engineering education, are mainly covered under the scope of this article.

Methods

This article explores key approaches through which sustainable engineering education has been integrated within one of the leading international Pan-African universities to contribute toward the United Nations' Sustainable Development Goals (SDGs). The methodology primarily focuses on identifying, documenting, and presenting institutional and academic practices that contribute toward embedding the United Nations' Sustainable Development Goals (SDGs) within the engineering curriculum, teaching, learning, and project work.

A qualitative and exploratory approach was adopted to illustrate how sustainability concepts have been promoted, implemented, and aligned with the university's Strategic Plan 2035, which highlights societal impact and sustainability as core pillars. The initiatives discussed represent structured efforts to move beyond conventional technical education and to nurture values of responsibility, ethics, and sustainability among both students and faculty.

Information was gathered from institutional activities, curriculum reforms, classroom practices, and sustainability-focused student and faculty projects. The selected examples showcase how sustainability principles have been woven into teaching and learning processes, and how these initiatives have collectively strengthened the university's contribution toward the SDGs.

The scope of this article includes efforts to reform curricula by introducing sustainability-related content, the execution of sustainability-oriented projects addressing real-world challenges, and the use of generative AI tools to enhance teaching, research, and publication in sustainable engineering education. The methodology is therefore descriptive and demonstrative in nature, aimed at sharing institutional experiences, highlighting effective practices, and encouraging further academic engagement in advancing sustainability-driven engineering education.

Result And Discussion

Works to Leveraging Sustainability in Mechanical Engineering Education

The term sustainability incorporates three aspects, society, economy, and environment (Purvis et al., 2019). Strengthening any of these three aspects or pillars leads to shaping a better world, which was the main intention behind setting the UN's SDGs in 2015. The main goal of sustainability is to achieve benefits to society, growth of economy, and protection of the environment. In other words, working towards sustainability positively impacts people, profit, and planet. Sustainable education is the basic and prime tool to achieve the goals of sustainability. Sustainable education can impart to learners and lecturers a sense of responsibility to contribute towards sustainability and adopt such practices that can facilitate people, profit, and planet. Sustainability-integrated teaching, learning, project, and research activities can be related to SDGs and documented further towards measuring the impact. The factors such as strict environmental regulations, accelerated competitiveness, and global reputation, etc. have made every sector in the world attempt to incorporate sustainability interventions. The education sector is one of the prime sectors where institutes and universities are aligning their plans and strategic objectives with sustainability. Sustainable education plays a big role in institutes and universities to achieve their objectives and targets, which are mainly aligned with sustainability these days.

The important ways to leverage sustainability are highlighted in this section with examples of work carried out at an international university. Restructuring curriculum and contents of the modules relating to SDGs; incorporating sustainability aspects such as economy, society, and environment, into project and research; and digital technology-based rapid accomplishment of academic and administration tasks, are some of the ways to leverage sustainability in engineering education.

Sustainability Integrated Teaching and Learning

It is easy to embed sustainability with the classical contents of any engineering module. Engineering curricula need proper identification and documentation to be enriched with the SDGs. Some important examples from mechanical engineering education are considered here. Module content-specific SDGs can be identified, and further content reform or regulation change can be done to incorporate sustainability in engineering education. Materials science and manufacturing engineering are the two most important modules of mechanical engineering. The most relevant SDGs to both modules are SDG-3 good health and well-being SDG-8 decent work and economic growth; SDG-9 industry, innovation, and infrastructure; SDG-12 responsible production and consumption. It is worth mentioning that SDG-17 partnership for the goals is a key goal that can greatly help to achieve other SDGs. An attempt has been made by us to promote sustainability-based mechanical engineering education by enriching contents of some modules with sustainability. We have restructured those modules to provide some basic knowledge of sustainability and SDGs and further included exercises, examples, and assessments that lead to generating and evaluating knowledge of sustainability. Figure 2 presents classical contents of manufacturing module before curriculum reform as well as revised contents enriched with sustainability and SDGs.

Manufacturing Engineering Module Basic Contents	Manufacturing Engineering Module with Sustainability and SDG Contents
Unit 1 Introduction Introduction to Engineering Materials, Manufacturing Processes, and Industrial Safety.	**Unit 1 Introduction** Introduction to Engineering Materials, Manufacturing Processes, and Industrial Safety. Introduction to Advanced Manufacturing, Industry 4.0, Sustainability, Sustainable development goals 'SDGs', and Green/Sustainable Manufacturing (Manufacturing aligned to Sustainable Development Goals).
Unit 2 Welding Classification of Joining and welding, welding definition, introduction, advantages and limitations, welding positions Fusion welding Gas welding, Arc welding, TIG welding, MIG welding, Resistance welding- spot welding, seam welding Solid state welding Roll welding, Forge welding, Friction welding, Ultrasonic welding Welding joints and symbols, Welding defects	**Unit 2 Welding** Classification of Joining and welding, welding definition, introduction, advantages and limitations, welding positions Fusion welding Gas welding, Arc welding, TIG welding, MIG welding, Resistance welding- spot welding, seam welding Solid state welding Roll welding, Forge welding, Friction welding, Ultrasonic welding Optimization of welding parameters for energy and resource efficiency Welding joints and symbols, Welding defects Preventive and corrective measures to minimize welding defects for sustainability
Unit 3 Casting Introduction to casting and foundry, classification of casting Expandable mold type casting Sand casting: general steps, sand molds, patterns, gating system and core, foundry sand and binders, sand and mold properties, furnaces for casting Shell molding, Investment casting, Permanent mold casting Die casting: cold chamber and hot chamber die casting Centrifugal casting: true centrifugal, semi centrifugal, centrifuge castings General defects in casting	**Unit 3 Casting** Introduction to casting and foundry, classification of casting Expandable mold type casting Sand casting: general steps, sand molds, patterns, gating system and core, foundry sand and binders, sand and mold properties, furnaces for casting. New Green materials for Casting molds Shell molding, Investment casting Permanent mold casting Die casting: cold chamber and hot chamber die casting Centrifugal casting: true centrifugal, semi centrifugal, centrifuge castings General defects in casting Green Casting Technologies
Unit 4 Bulk Deformation Processes Introduction, difference between bulk deformation and sheet metal operations Rolling: introduction to general working principle, flat and shape rolling, hot and cold rolling, rolling mills, ring rolling, thread rolling, Forging: introduction and classification, open die forging, closed die forging, forging hammers and press, other deformation processes related to forging- upset forging and heading Extrusion: Introduction, hot extrusion- direct extrusion and indirect extrusion, cold extrusion- impact extrusion, hydrostatic extrusion Bar and Wire Drawing	**Unit 4 Bulk Deformation Processes** Introduction, difference between bulk deformation and sheet metal operations Rolling: introduction to general working principle, flat and shape rolling, hot and cold rolling, rolling mills, ring rolling, thread rolling, Forging: introduction and classification, open die forging, closed die forging, forging hammers and press, other deformation processes related to forging- upset forging and heading Extrusion: Introduction, hot extrusion- direct extrusion and indirect extrusion, cold extrusion- impact extrusion, hydrostatic extrusion Bar and Wire Drawing Reuse, Remanufacture, and recycling of Dies
Unit 5-Metal Cutting (Machining) Metal cutting introduction and mechanism, cutting tools and fluids, machine tools Turning- Straight turning, Taper turning, Chamfering, Knurling, Parting-off Milling- Horizontal and vertical milling operations Drilling operations- Drilling, Reaming, Countersinking, Counterboring, Tapping	**Unit 5-Metal Cutting (Machining)** Metal cutting introduction and mechanism, cutting tools and fluids, machine tools. Green lubricants, Sustainable Lubrication Techniques (Dry and Near-dry machining) Turning- Straight turning, Taper turning, Chamfering, Knurling, Parting-off Milling- Horizontal and vertical milling operations Drilling operations- Drilling, Reaming, Countersinking, Counterboring, Tapping
Unit 6-Powder Metallurgy Introduction, parts made by powder metallurgy, advantages and limitations Engineering powders and their production Powder metallurgy process steps- Bending and Mixing, Pressing, Sintering, Sizing	**Unit 6-Powder Metallurgy** Introduction, parts made by powder metallurgy, advantages and limitations Engineering powders and their production Powder metallurgy process steps- Bending and Mixing, Pressing, Sintering, Sizing Optimization of powder metallurgy process to achieve reduced process chain for Sustainability

Fig. 2 - Example of inclusion of sustainability-based content in manufacturing engineering module

The contents added to bring the texture of sustainability are mainly basics of sustainability and SDGs, which were added to the beginning of the module. Further, some more contents were added to other chapters belonging to various aspects of sustainability targeting SDGs 3, 9, and 12.

Another important intervention took place in final year module 'research methodology' where in one of the assessments, students were given a task of *SDG mapping* of their final year project. The task that was given is as follows:

"Please perform sustainability mapping for your honours project in terms of relating your project with any of the two sustainable development goals (SDGs) and briefly explain in what way your project contributes towards those SDGs? Which pillar of sustainability can your project strengthen? Briefly explain."

From the students, very interesting and creative responses, as shown in Fig. 3, were recorded and marked.

Question 2 **Student Script Example 1**

a. My project focus on developing an adequate infrastructure building for educational facilities. My aim is to develop a design that is easy to assemble using sustainable material and able to control the indoor climate. This connects to several Sustainable Development Goals (SDGs), in this case I will focus on SDG 9: Industry, Innovation, and Infrastructure and SDG 13:Climate Action since they align with my goals and objectives of creating a sustainable and efficient educational facility that contributes to environmental sustainability and infrastructure development. The SDG set by the United Nation have specific targets to measure progress towards achieving SDG and my project align with those goals and targets in the following way:

SDG 9: Industry, Innovation, and Infrastructure
This focusses on supporting innovation, encouraging inclusive and sustainable industrialisation, and creating infrastructure that is durable.

Project Contribution:
My modular classroom project supports several goals under SDG 9 (Industry, Innovation, and Infrastructure), which includes Target 9.1, Target 9.4, and Target 9.5. My project aims to create sustainable and strong infrastructure that provides reliable educational facilities capable of withstanding extreme hot climate, addressing infrastructures at schools and the well-being of learners and students. It also focuses on energy efficiency by using solar panels and eco-friendly materials, which supports Target 9.4, promoting the efficient use of resources and clean technologies. And my project encourages research and innovation in climate-responsive design and sustainable building methods, helping to meet Target 9.5. This project plan reduces environmental impact and provides a model that can be used for similar projects.

Figure 1: SDG 9: Industry, Innovation and Infrastructure(United Nation, 2025)

Student Script Example 2

I have two relevant SDGs for my honours design project, "Design for Maintainability: A Small-Scale Coal Mining Vibrating Screen". With the integration of these sustainable considerations, the project does not only advance technological innovation in mining but also contributes meaningfully to more environmental and economic goals. These relevant sustainable development goals are SDG 9 and SDG 12, with their relevant targets.

1. SDG 9: Industry, Innovation and Infrastructure.

SDG 9 is just about building strong infrastructure, supporting industries and encouraging innovation to help with economic growth. To improve the lives of people and protect the environment, they need better infrastructure that will last longer. This goal also focuses on making sure that companies create jobs for everyone and use eco-friendly technology.

My design project contributes to SDG 9 because I will be designing a more efficient and maintainable vibrating screen for small-scale coal mining companies. An innovative design as I will be implementing predictive maintenance with machine learning with the aim of improving the reliability of equipment and reduces unexpected breakdowns. I will be designing a more durable and cost-effective coal vibrating screen that supports sustainable ming operations, reducing production downtime and increasing productivity.

1.1. Target 9.4: The upgrade of infrastructure and retrofit industries by making them more sustainable with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.

2. SDG 12: Responsible Consumption and Production

My design project aligns with SDG 12 as it is promoting energy-efficient and sustainable mining machines. The improved design will reduce material waste by minimizing frequent part replacements.

3. Pillars of sustainability that strengthens my project:

3.1. Environmental Sustainability:

- My design project promotes energy efficiency and waste reduction as I am designing a coal mining vibrating screen that lasts longer and requires less repairs.
- The use of predictive maintenance reduces the carbon footprint by minimizing unnecessary material use and energy waste.

3.2. Economic Sustainability:

- The small-scale coal mining companies will benefit from reduced maintenance costs and increased productivity therefor making sure that mining companies can keep running and making money for a longtime without financial problems.

Fig. 3 - Examples of student responses on SDG mapping of their projects

The assessment turned out to be a great success from the viewpoint of a deeper understanding and learning of the students about sustainability, its importance, linking projects with SDGs and making contributions towards shaping a better world.

Projects Based on Sustainability

Sustainability-integrated projects can easily be designed for a better understanding of the learners and real-world experiences so that they can realize the importance of sustainability interventions to support and make contributions towards climate action, economic growth, and societal development. Encouraging learners to pursue interdisciplinary engagements and partnerships with each other is also helpful to make best out of this intervention. Some of the important examples of engaging learners in sustainability projects are mainly related to safety, environment protection, clear and green environment. We have assigned such projects to our industrial engineering technology final-year students in the last few years. Some of the important examples are discussed here.

To enable industrial engineering learners to make contributions towards SDGs, some problems have been identified at the university workspaces related to ergonomics, orderliness, layouts, health, and safety. Targeting SDG 3 good health and well-being and SDG 8 decent work and economic growth, lean manufacturing interventions, ergonomic techniques, and other industrial engineering tools were employed to re-solve those issues and achieve clean, green, and safe university workplace.

Figure 4 presents some of the project examples aligned with various SDGs. Similarly, mechanical engineering students were also assigned such tasks and they completed projects such as green machining of difficult-to-machine materials, aligned with SDG 9 industry, innovation, and infrastructure, and SDG 12 responsible production and consumption.

In addition to that, all project rubrics, for mechanical engineering, incorporate sustainability evaluations, where the students need to justify their contributions aligned with the criterion such as sustainability analysis, and environmental, economic, and social impact assessments, of the product or system design under consideration. These factors are governed based on the graduate attribute 7 sustainability and im-pact of engineering activity. Figure 5 provides the blurb of the rubric having sustainability indicators and their evaluation for final-year projects.

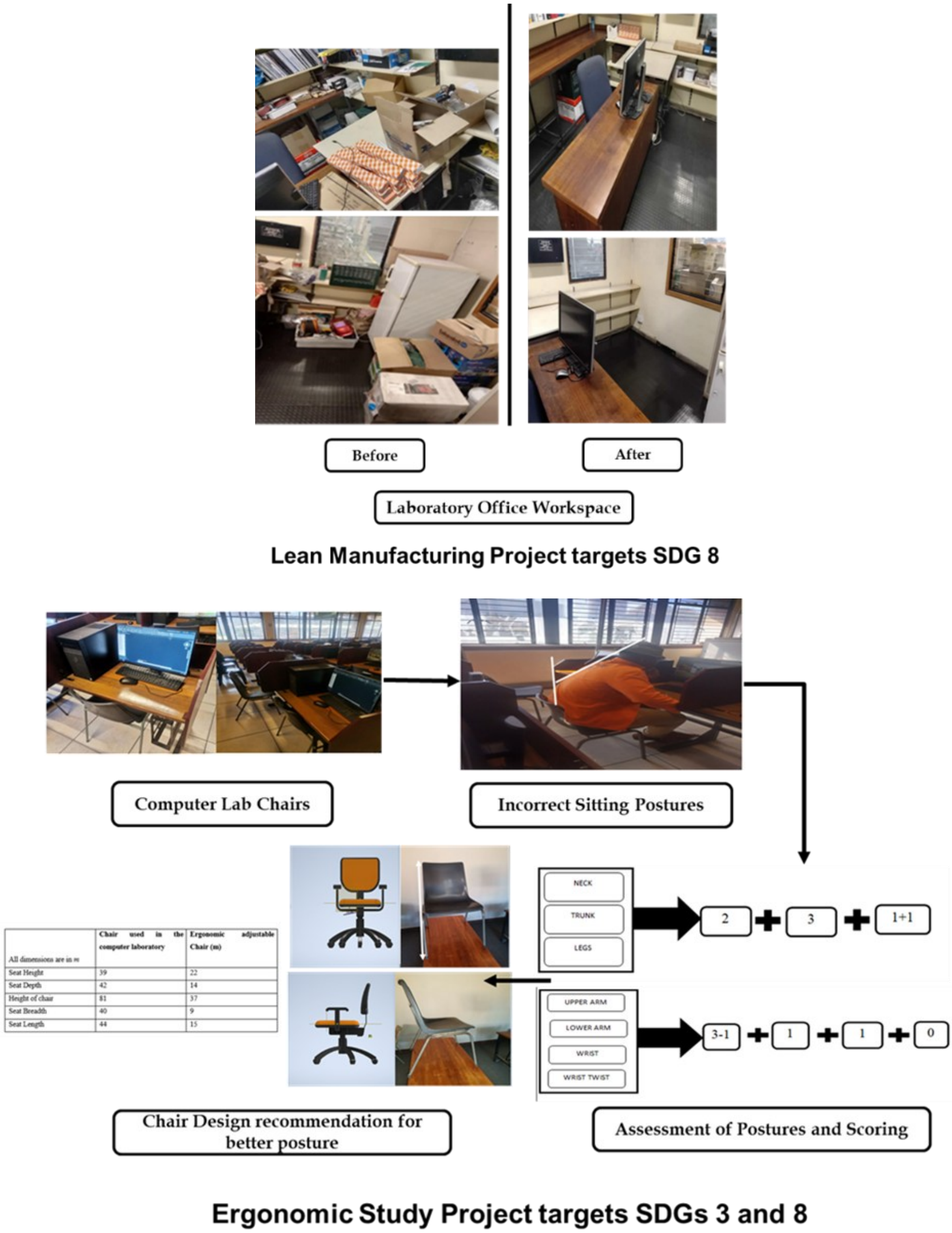
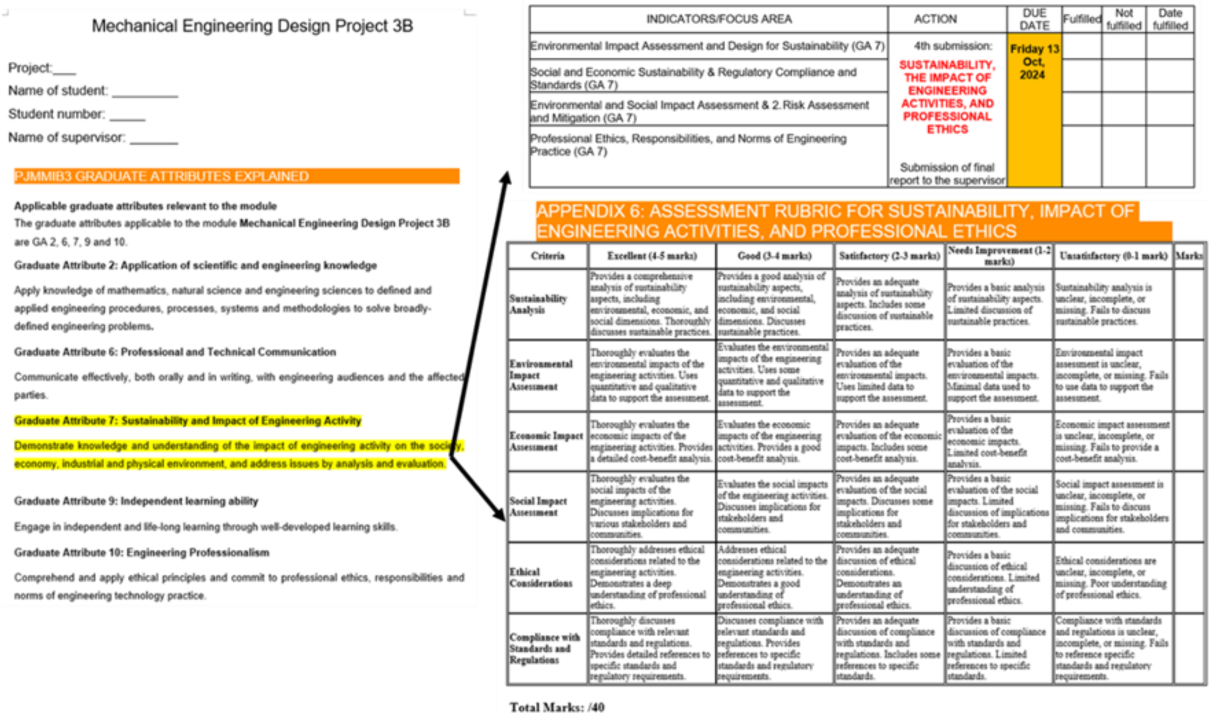


Fig. 4 - Examples of industrial engineering undergraduate projects targeting various SDGs.



Mechanical Engineering Design Project 3B

Project:___
Name of student: _________
Student number: _____
Name of supervisor: _______

PJMMIB3 GRADUATE ATTRIBUTES EXPLAINED

Applicable graduate attributes relevant to the module
The graduate attributes applicable to the module **Mechanical Engineering Design Project 3B** are GA 2, 6, 7, 9 and 10.

Graduate Attribute 2: Application of scientific and engineering knowledge

Apply knowledge of mathematics, natural science and engineering sciences to defined and applied engineering procedures, processes, systems and methodologies to solve broadly-defined engineering problems.

Graduate Attribute 6: Professional and Technical Communication

Communicate effectively, both orally and in writing, with engineering audiences and the affected parties.

Graduate Attribute 7: Sustainability and Impact of Engineering Activity

Demonstrate knowledge and understanding of the impact of engineering activity on the society, economy, industrial and physical environment, and address issues by analysis and evaluation.

Graduate Attribute 9: Independent learning ability

Engage in independent and life-long learning through well-developed learning skills.

Graduate Attribute 10: Engineering Professionalism

Comprehend and apply ethical principles and commit to professional ethics, responsibilities and norms of engineering technology practice.

INDICATORS/FOCUS AREA	ACTION	DUE DATE	Fulfilled	Not fulfilled	Date fulfilled
Environmental Impact Assessment and Design for Sustainability (GA 7)	4th submission: SUSTAINABILITY, THE IMPACT OF ENGINEERING ACTIVITIES, AND PROFESSIONAL ETHICS Submission of final report to the supervisor	Friday 13 Oct, 2024			
Social and Economic Sustainability & Regulatory Compliance and Standards (GA 7)					
Environmental and Social Impact Assessment & 2. Risk Assessment and Mitigation (GA 7)					
Professional Ethics, Responsibilities, and Norms of Engineering Practice (GA 7)					

APPENDIX 6: ASSESSMENT RUBRIC FOR SUSTAINABILITY, IMPACT OF ENGINEERING ACTIVITIES, AND PROFESSIONAL ETHICS

Criteria	Excellent (4-5 marks)	Good (3-4 marks)	Satisfactory (2-3 marks)	Needs Improvement (1-2 marks)	Unsatisfactory (0-1 mark)	Marks
Sustainability Analysis	Provides a comprehensive analysis of sustainability aspects, including environmental, economic, and social dimensions. Thoroughly discusses sustainable practices.	Provides a good analysis of sustainability aspects, including environmental, economic, and social dimensions. Discusses sustainable practices.	Provides an adequate analysis of sustainability aspects. Includes some discussion of sustainable practices.	Provides a basic analysis of sustainability aspects. Limited discussion of sustainable practices.	Sustainability analysis is unclear, incomplete, or missing. Fails to discuss sustainable practices.	
Environmental Impact Assessment	Thoroughly evaluates the environmental impacts of the engineering activities. Uses quantitative and qualitative data to support the assessment.	Evaluates the environmental impacts of the engineering activities. Uses some quantitative and qualitative data to support the assessment.	Provides an adequate evaluation of the environmental impacts. Uses limited data to support the assessment.	Provides a basic evaluation of the environmental impacts. Minimal data used to support the assessment.	Environmental impact assessment is unclear, incomplete, or missing. Fails to use data to support the assessment.	
Economic Impact Assessment	Thoroughly evaluates the economic impacts of the engineering activities. Provides a detailed cost-benefit analysis.	Evaluates the economic impacts of the engineering activities. Provides a good cost-benefit analysis.	Provides an adequate evaluation of the economic impacts. Includes some cost-benefit analysis.	Provides a basic evaluation of the economic impacts. Limited cost-benefit analysis.	Economic impact assessment is unclear, incomplete, or missing. Fails to provide a cost-benefit analysis.	
Social Impact Assessment	Thoroughly evaluates the social impacts of the engineering activities. Discusses implications for various stakeholders and communities.	Evaluates the social impacts of the engineering activities. Discusses implications for stakeholders and communities.	Provides an adequate evaluation of the social impacts. Discusses some implications for stakeholders and communities.	Provides a basic evaluation of the social impacts. Limited discussion of implications for stakeholders and communities.	Social impact assessment is unclear, incomplete, or missing. Fails to discuss implications for stakeholders and communities.	
Ethical Considerations	Thoroughly addresses ethical considerations related to the engineering activities. Demonstrates a deep understanding of professional ethics.	Addresses ethical considerations related to the engineering activities. Demonstrates a good understanding of professional ethics.	Provides an adequate discussion of ethical considerations. Demonstrates an understanding of professional ethics.	Provides a basic discussion of ethical considerations. Limited understanding of professional ethics.	Ethical considerations are unclear, incomplete, or missing. Poor understanding of professional ethics.	
Compliance with Standards and Regulations	Thoroughly discusses compliance with relevant standards and regulations. Provides detailed references to specific standards and regulatory requirements.	Discusses compliance with relevant standards and regulations. Provides references to specific standards and regulatory requirements.	Provides an adequate discussion of compliance with standards and regulations. Includes some references to specific standards.	Provides a basic discussion of compliance with standards and regulations. Limited references to specific standards.	Compliance with standards and regulations is unclear, incomplete, or missing. Fails to reference specific standards and regulatory requirements.	

Total Marks: /40

Fig. 5 - Highlighted sustainability indicators for evaluation of mechanical engineering final-year projects.

AI in Sustainable Engineering Education

The 4th industrial revolution is shaped by digital technologies, with artificial intelligence (AI) as the backbone. Tools such as digital twins, virtual and augmented reality, simulations, generative AI, and 3D printing have proven effective in advancing quality education and societal impact (Bula Bunjaku et al., 2024), (Gupta, 2023). Generative AI and simulations support high-quality projects, research, and publications, while VR, AR, digital twins, and 3D printing enhance teaching through improved content development and delivery.

Virtual reality enables effective online and remote learning, demonstrated by a virtual manufacturing lab for mechanical engineering students. Likewise, 3D printing is widely used for prototyping, laboratory samples, and project demonstrations (Espach & Gupta, 2023). Augmented reality deepens learner understanding by providing detailed insights into mechanical parts and systems. Generative AI, if used ethically, offers significant time savings by assisting students and researchers with idea generation, creative outputs, and feedback. When integrated with sustainability, AI-based education can strengthen the economy, protect the environment, and promote social inclusion. Remote and flexible learning reduces carbon footprints, optimizes resource use, and expands access to underserved groups, aligning with eco-friendly and equitable education goals.

In practice, generative AI has been incorporated into the 'research methodology' module for bachelor's students in mechanical and industrial engineering. Learners used AI tools such as ChatGPT for project proposals, research plans, and presentations, alongside reference managers like Mendeley and Endnote. Tools like Elicit and Research Rabbit supported literature review and analysis. Training sessions ensured students understood institutional policies and emphasized ethical AI use. Informal feedback revealed high satisfaction, with students reporting that these digital tools significantly reduced administrative tasks and improved efficiency.

Conclusion

Sustainable engineering education is not just a response to global challenges but a proactive approach to creating resilient and equitable systems for future generations. By embedding sustainability principles into engineering curricula, fostering interdisciplinary collaboration, and leveraging digital tools, educational institutions can pre-pare engineers who can make positive contributions to a sustainable future. As the world faces unprecedented environmental and social pressures, the role of sustainable engineering education becomes increasingly vital in shaping the leaders and innovators of tomorrow.

The following key points can be summarized:

- Incorporating sustainability-related content in various courses has been found effective and led to further maximizing the future attempts towards a meaningful and best contribution to SDGs.
- Undergraduate-level projects based on solving the university issues and achieving sustainability have been found effective and creative enough for the students to gain sustainability insights and make a societal impact.
- The outcomes of such projects, due to their inherent nature, promoted decent work and economic growth, good health and well-being, and responsible production and consumption, type SDGs.
- Digital technology interventions for research, projects, and publications have also greatly assisted the students.
- Training and upskilling for sustainability and digitalization, ensured the awareness, understanding, and knowledge among students and staff to establish the field further.

Conclusively, the attempts to leverage sustainability in engineering education, as discussed in this article, contributed to the strategic goals of the university and increased its impact on pursuing sustainable development goals. Such interventions can be scaled to other engineering institutions and universities to achieve excellence and sustainability.

References

Acosta-Castellanos, P. M., Queiruga-Dios, A., and Camargo-Mariño, J. A. "Environmental Education for Sustainable Development in Engineering Education in Colombia." *Frontiers in Education* 9 (2024): 1306522. https://doi.org/10.3389/feduc.2024.1306522.

Barrio, J., Acha, V. L., Agirre, E., and Viar, N. "Integration of Sustainable Development Goals in the Field of Process Engineering through Active Learning Methodologies." *Education for Chemical Engineers* 49 (2024): 26–34. https://doi.org/10.1016/j.ece.2024.01.005.

Bula Bunjaku, I., Gagica, S., and Doyle Kent, M. "Integrating Digital Tools in Engineering Education: Social Impact of Technological Integration." *IFAC-PapersOnLine* 58, no. 3 (2024): 118–122. https://doi.org/10.1016/j.ifacol.2024.01.002.

Chen, H., Wang, S., and Li, Y. "Aligning Engineering Education for Sustainable Development through Governance: The Case of the International Center for Engineering Education in China." *Sustainability* 14, no. 21 (2022): 14643. https://doi.org/10.3390/su142114643.

Espach, A., and Gupta, K. "3D Printing—An Important Industry 4.0 Tool for Online and Onsite Learning." In *Artificial Intelligence and Online Engineering: REV 2022*, edited by M. E. Auer,

S. A. El-Seoud, and O. H. Karam, Lecture Notes in Networks and Systems, vol. 524. Cham, Switzerland: Springer, 2023. https://doi.org/10.1007/978-3-031-17091-1_32.

Fishlock, S., Thompson, M., and Grewal, A. "Sustainable Engineering Design in Education: A Pilot Study of Teaching Right-to-Repair Principles through Project-Based Learning." *Global Challenges* 7 (2023): 2300158. https://doi.org/10.1002/gch2.202300158.

Fredriksson, C., and Dwek, M. "Sustainable Development in Engineering Education." In *Proceedings of the 2021 World Engineering Education Forum/Global Engineering Deans Council (WEEF/GEDC)*, 1–6. Madrid, Spain, 2021. https://doi.org/10.1109/WEEF/GEDC53299.2021.9657227.

García-Aranda, C., Molina García, A., Pérez Rodríguez, J., and Rodríguez-Chueca, J. "Sustainability in Engineering Education: Experiences of Educational Innovation." In *Handbook of Sustainability Science in the Future*, edited by W. Leal Filho, A. M. Azul, F. Doni, and A. L. Salvia. Cham, Switzerland: Springer, 2023. https://doi.org/10.1007/978-3-030-68074-9_153-1.

Gómez-Martín, M. E., Gimenez-Carbo, E., Andrés-Doménech, I., and Pellicer, E. "Boosting the Sustainable Development Goals in a Civil Engineering Bachelor Degree Program." *International Journal of Sustainability in Higher Education* 22, no. 8 (2021): 125–145. https://doi.org/10.1108/IJSHE-02-2021-0065.

Gudonienė, D., Paulauskaitė-Tarasevičienė, A., Daunorienė, A., and Sukackė, V. "A Case Study on Emerging Learning Pathways in SDG-Focused Engineering Studies through Applying CBL." *Sustainability* 13, no. 15 (2021): 8495. https://doi.org/10.3390/su13158495.

Gupta, K. "Some Techniques for Smart Engineering Education." In *Artificial Intelligence and Online Engineering: REV 2022*, edited by M. E. Auer, S. A. El-Seoud, and O. H. Karam, Lecture Notes in Networks and Systems, vol. 524. Cham, Switzerland: Springer, 2023. https://doi.org/10.1007/978-3-031-17091-1_38.

Gutierrez-Bucheli, L., Kidman, G., and Reid, A. "Sustainability in Engineering Education: A Review of Learning Outcomes." *Journal of Cleaner Production* 330 (2022): 129734. https://doi.org/10.1016/j.jclepro.2021.129734.

Hąbek, P., Palacz, M., and Saeed, F. "Embedding Sustainability into Mechanical Engineering Master Programs: A Case Study of the Top Technical Universities in Europe." *Sustainability* 16, no. 2 (2024): 941. https://doi.org/10.3390/su16020941.

Isaza Domínguez, L. G., Velasquez Clavijo, F., Robles-Gómez, A., and Pastor-Vargas, R. "A Sustainable Educational Tool for Engineering Education Based on Learning Styles, AI, and Neural Networks Aligning with the UN 2030 Agenda for Sustainable Development." *Sustainability* 16, no. 20 (2024): 8923. https://doi.org/10.3390/su16208923.

Purvis, B., Mao, Y., and Robinson, D. "Three Pillars of Sustainability: In Search of Conceptual Origins." *Sustainability Science* 14 (2019): 681–695. https://doi.org/10.1007/s11625-018-0627-5.

Pujol, F. A., and Tomás, D. "Introducing Sustainability in a Robotic Engineering Degree: A Case Study." *Sustainability* 12, no. 14 (2020): 5574. https://doi.org/10.3390/su12145574.

Ramirez-Mendoza, R. A., Morales-Menendez, R., Melchor-Martinez, E. M., et al. "Incorporating the Sustainable Development Goals in Engineering Education." *International Journal of Interactive Design and Manufacturing* 14 (2020): 739–745. https://doi.org/10.1007/s12008-020-00661-0.

Times Higher Education. *Impact Rankings*. https://www.timeshighereducation.com/impactrankings (accessed January 31, 2025).

Tisdale, J. K., and Bielefeldt, A. R. "Exploring Sustainability Instruction Methods in Engineering Thermodynamics Courses: Insights from Scholarship of Teaching and Learning." *Sustainability* 16, no. 19 (2024): 8637. https://doi.org/10.3390/su16198637.