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Embedding Sustainability into Mechanical Engineering Master Programs—A Case Study of the Top Technical Universities in Europe

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Abstract: Considering the vital role of higher education institutions (HEIs) in accomplishing sustainable development goals, this study examines the ways in which sustainability is integrated into mechanical engineering master's programs in the selected top technical universities in the EU. The content analysis was employed to evaluate the universities' commitment to sustainability and approach to integrating sustainability into mechanical engineering programs. The Sustainability Tracking, Assessment, and Rating SystemTM (STARS) credit AC1 was used as a reference to categorise the courses into sustainability-focused courses (SF) and courses that include sustainability content (SI). We used the Sustainability Tool for Auditing University Curricula in Higher Education (STAUNCH) to identify the sustainability-related topics integrated into the mechanical engineering programs. The empirical findings indicate that while all three top technical universities in Europe demonstrate a comprehensive commitment to sustainability, their approaches for integrating sustainability into their mechanical engineering master's programs vary, leaving room for further improvements. The paper thoroughly analyses the top technical universities' sustainability efforts, offering valuable insights for educators and institutions seeking to enhance sustainability integration in higher education curricula.

Keywords: higher education; sustainability; engineering education; curricula; mechanical engineering program; technical universities

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1. Introduction

It is widely acknowledged that one of the most significant societal issues of the twenty-first century is sustainable development. Higher education institutions have the insight, the know-how, and the authority to steer this change and bring about the adjustments necessary for this new paradigm. As a result, the mission and practice of higher education institutions must embrace sustainability values. Although there are some documented successful case studies, there are no consolidated techniques to enable an integrated and comprehensive implementation of sustainability or to pinpoint the potential linked to this process [1]. Environmental and social knowledge with inter abilities like integrity and logical analysis is the foundation of sustainable development education. It is crucial to promote sustainable development in all academic settings [2]. In many higher education institutions, there has been substantial progress in incorporating sustainability into research, buildings, and operations. However, many universities are struggling to integrate sustainable development into their engineering education curricula [3].

Curricular assessments in the field of education look at the inclusion of sustainability-related elements in the curriculum. Assessments of the curriculum reveal how much sustainability is incorporated into courses, which can provide university administrators with a jumping-off point for reform. However, as shown by the various assessment methods available to higher education, there is still no agreement on how to evaluate the inclusion of sustainability in the curricula [4]. The mechanical engineering profession is crucial in solving sustainability concerns and promoting sustainable civilisation growth. Graduates must gain the knowledge and abilities necessary to offer original solutions to current problems. The idea of sustainable design and manufacturing should be covered in mechanical engineering's core (mandatory) design and manufacturing modules. This will not only enhance the academic field but also accelerate the pace at which mechanical engineers in the community tackle societal challenges, providing sustainability. Therefore, we formulated four research questions that are central to the empirical part of the paper:

RQ1: How do the institutional frameworks of the Politecnico di Milano, the Technical University of Munich, and the University of Manchester differ in terms of commitment to sustainability?
RQ2: How is sustainability-related content integrated into mechanical engineering programs?
RQ3: What are the sustainability-related topics that are integrated into the program of mechanical engineering?
RQ4: Which part of the courses' syllabuses are the sustainability-related topics located in?

The rest of the paper is structured as follows: the next section provides an overview of integrating sustainability into higher education programs, particularly emphasising mechanical engineering education. This is followed by a section dedicated to the methodology used in the research process. The research findings regarding the institutional commitment to sustainability and the approaches employed by the universities in integrating sustainability into their mechanical engineering programs are then presented. The paper ends with a discussion and conclusions, including limitations as well as recommendations for further research.

2. Literature Review

2.1. Higher Education and the Need for Incorporating Sustainability into Curricula

The importance of higher education in fostering a shift to a more sustainable society cannot be overstated [5,6]. The social system recognises the need to promote new behaviours and strive for sustainable growth more urgently than ever. Institutions of higher education are seen as crucial to achieving sustainability and sustainable development goals [7–9]. The goal of higher education for sustainable development is to equip students with the knowledge and enable them to gain the skills they need to lead society's transformation to sustainability [10,11]. Higher education graduates can help with the shift toward sustainability [4]. However, such a change needs the university education to be revised or reconstructed. Unfortunately, higher education institutions still do not take sustainability theories seriously in their curricula [12,13].

Numerous researchers have investigated ways to integrate sustainable development into university curricula [14–17]. They include a wide range of integration techniques and determinants of success in relation to engagement, teaching, development, and institutional functions [18,19]. Many of them concluded that their primary goal was to foster an attitude of inquiry and innovative thinking rather than simply imparting fundamental technical information while instructing their students [20]. Consequently, students frequently match their impressions with those of their instructors and the active learning strategies they choose to use while in university [21]. It must be admitted that university education faces difficulty in preparing graduates with the practice and implementation of sustainability at a time of substantial environmental challenges around the world and the need for sustainable development.

2.2. Integrating Sustainability into Engineering Education

The necessity of incorporating sustainability into education is strongly advocated [22]. The United Nations Decade of Education for Sustainable Development started the Global Action Program because they realised how crucial it was to continue this endeavour. The necessity for mentoring and assessing initiatives to reorient education systems was noted in the most recent report from UN DESD [23]. This was listed as one of the most persistent problems that needed to be solved in the same study.

Over the past ten years, the global engineering education community has become increasingly aware of sustainability and its proper place in engineering education. Although calls for integrating sustainability and sustainable development content into mechanical engineering curricula made since the 1990s, according to the literature on education for sustainability, there has not been much in the way of strategic and systemic integration, which has delayed the integration of sustainability knowledge and skills. In this highly regulated field, which is often run by professional engineering institutions (PEIs), it is evident from the literature on curriculum renewal that accreditation is a crucial factor in guiding and overseeing curriculum renewal. Furthermore, it is evident that PEIs take an active role in addressing present and foreseeable societal demands. Therefore, it is envisaged that PEIs will consider the challenge of appropriately incorporating sustainability over future accreditation reviews and guideline iterations, given the global drivers for engineers to produce sustainable solutions. Several PEIs have already incorporated sustainable language into their codes of conduct and graduation competence statements [24]. Ref. [25] emphasised the need for professional engineering programs worldwide to quickly update their curricula to address gaps in key competencies in current programs, considering the manifesting signs of the present unsustainable societal construct such as climate change. It is essential that both academics involved in developing and delivering programs and in accrediting PEIs support this. The necessity for sustainable themes and concepts in accrediting requirements across all fields is evolving in step with broader cultural and political expectations. While homogeneity in this developing subject is neither conceivable nor desirable, the authors argue that it is both possible and desirable to be prepared for the second decade of the twenty-first century and beyond, so professional engineering programs should incorporate each of the sustainability concepts. However, to produce sustainable mechanical engineers, a significant curriculum adjustment will be necessary. Graduates who will view themselves as ethical professionals with a responsibility to society as opposed to merely being paid labourers serving as largely uncritical agents of the client will be the outcome of this change. By its very nature, such a curriculum will clearly evaluate the engineer's beliefs, ethics, and social responsibility in a wider context than before and develop abilities for interdisciplinary effort [26,27].

2.3. Sustainability in Mechanical Engineering Education

Mechanical engineering programs must comply with reputable accrediting standards, notably the EUR-ACE (European Network for Accreditation of Engineering Education) [28]. It includes specifications on how mechanical engineers must strengthen sustainable development. The EUR-ACE illustrates an understanding of the healthcare, legalities, and duties of engineering practice as well as the influence of engineering solutions on society and the environment and adheres to professional conduct, responsibilities, and standards of engineering practice [29].

Mechanical engineers are essential in putting technological innovations into operation that can solve present issues and promote sustainable development [30]. Hence, they are currently leading the charge for socioeconomic imperatives [31]. Focusing on the technical components of engineering knowledge and applying technical knowledge to sustainability objectives (e.g., necessary training to conduct life cycle assessments) is a crucial topic that needs to be addressed [32,33].

According to the Barcelona Declaration [34], mechanical engineers must be able to comprehend how their profession relates to society and the environment in order to detect impediments, threats, and repercussions. They should recognise the significance of their projects in different cultural, social, and political circumstances. They should engage in multidisciplinary teams to modify present technologies to meet the needs of resource efficiency, social sustainability, and environmental conservation.

The requirement to include sustainability factors in the curriculum is already included in the deontological rules of professional mechanical engineering schools. Even if it is assumed that there can never be complete clarity on how technology will affect society, practitioners and institutions still have a duty to create new technologies that will have beneficial effects and increase rather than decrease human empowerment. When preparing mechanical engineering professionals, it is important to consider higher education institutions' commitment to education for sustainable development and their involvement in addressing sustainability concerns. In the past three decades, more than 1400 institutions have authorised, published, and signed more than thirty international statements, letters, or initiatives that demonstrate the recognition from a variety of fields that universities have a responsibility to address these concerns [35].

A pedagogical framework for mechanical engineering education begins by pointing out that the conversation on sustainability and sustainable development should go beyond its environmental and social origins because technology is a significant and fundamental driver of current human development and is inextricably woven into society [36]. One should not only see technology as a means of achieving predetermined equipment and system performance targets but also as having a profound impact on the dialogue. Mechanical engineering curricula's main objective now is to incorporate sustainability learning. In a 2009 poll of universities offering engineering degrees, 80% of participants reported engaging in some form of sustainability-related activity. Additionally, there is a rising need for engineers who are knowledgeable about sustainable technologies [37].

In order to increase the effectiveness of sustainability education in mechanical engineering, a significant body of prior research has examined a variety of instructional strategies, which includes project-based learning [38], guided-discovery learning [37], and problem-based learning [39]. The primary objective of the curriculum is to give students a thorough and all-encompassing understanding of the significance of sustainability as well as to introduce sustainability principles [40]. When students acquire the capacity to think creatively and critically and interact with many standpoints, they are intrinsically motivated to learn about sustainability. It will also explain how sustainability should be taken into account throughout the mechanical engineering, manufacturing, and design process. The idea of a sustainability mindset is described as a mode of thinking that transcends specialised skills and incorporates systemic methods connected to viability into engineering practice [41]. Along with promoting innovativeness in development and manufacturing processes, the curriculum should also include sustainability as a key limitation. Using a design-focused curriculum and initiatives, sustainability is primarily discussed in mechanical engineering. Numerous academics have noted the importance of comprehending individual perspectives and collective frames of reference to the effectiveness of design processes [42]. Mechanical engineers mostly follow a design mentality. They have a distinct attitude and use various techniques, which affects how innovative they are and how quickly they can finish challenging design engineering projects. Most studies on the mindsets of designers have mostly concentrated on innovation and the fundamental processes that support it [43].

The amount of course activity connected to sustainability and sustainable development varies across universities, although most offer some level of it. Initiatives often fall into one of two categories, which include those that seek to integrate sustainability into the curriculum or those that seek to improve the sustainability of universities themselves such as through sustainable campus design or sustainable purchasing [44]. Segalàs examined engineering students' perceptions of programs that place a strong emphasis on sustainable development across a number of European institutions and discovered that most of them view sustainability as a technological and environmental issue and very infrequently connect it to social or institutional factors [45]. They also discovered that before and after taking pertinent courses, students' perspectives alter somewhat. According to concept maps, three key themes for sustainability were "technology", "environmental", and "resources", respectively. It seems that the trans-disciplinary nature of sustainability and the overemphasis on environmental issues at the expense of economic and social issues may make it difficult to conduct education for sustainable development programs successfully [46].

Several papers focus on the challenges of incorporating sustainability into curricula [47–51]. Early attempts to incorporate sustainability into the curriculum mainly depended on vertical integration, which means that sustainability is integrated via specific sustainability-related courses [52]. With further practice, it was demonstrated that "across the curricular integration" offers several benefits. During a mechanical engineer's academic career, across curriculum integration, frequently called horizontal integration incorporates sustainability concepts into conventional engineering courses. This strategy was established to promote increased clarity and comprehension of the intended educational objectives [53]. According to the researchers of prior studies, when it comes to applying acquired theory to practical operations in the field, horizontal integration is preferable to vertical integration [54]. As an outcome, by including sustainability practices across the curriculum, graduates have a comprehensive grasp of the subject and are more equipped to use sustainable strategies when making mechanical engineering decisions.

3. Methodology

We used QS World University Ranking 2022 to select the top 10 universities in Europe within the subject area of Engineering and Technology. The study's main aim was to explore how sustainability is included in mechanical engineering programmes at those universities. We chose master's studies for analysis as the pilot study indicated that at the bachelor level, sustainability is rarely included in the study programme. All of the top 10 universities by QS World University ranking (subject: engineering and technology) offer mechanical engineering programmes for master's studies, but only 3 of 10 disclose programmes and syllabuses. We used content analysis to identify three groups of courses: sustainability-focused (SF) courses, sustainability-inclusive (SI) courses, and those where there is no evidence that the content is related to sustainability. Data were collected from course content, course description, aim, and learning outcomes delivered by syllabuses available on the websites of the Politecnico di Milano, the Technical University of Munich, and the University of Manchester.

To evaluate the universities' commitment to sustainability as institutions, we first examined their websites' content. We analyse the vision, mission, strategy, and sustainability strategy, if available, to develop a profile of each university based on the material that was released.

We used the STARS credit AC1 as a reference for the case studies. The Sustainability Tracking, Assessment, and Rating SystemTM (STARS) is a voluntary, self-reporting framework for helping track and measure sustainability progress in higher education. The STARS framework was developed by the Association for the Advancement of Sustainability in Higher Education [55]. STARS Credit AC1 refers to the course content. It proposes an inventory of courses with distinction to: (1) sustainability courses—SF (courses for which the primary focus is on sustainability and/or understanding or solving one or more major sustainability challenges), and (2) courses that include sustainability—SI (courses that are focused on a topic other than sustainability, but incorporate a unit or module on sustainability or a sustainability challenge, include one or more sustainability-focused activities, or integrate sustainability issues throughout the course). Curricular assessments gave us insight into the extent sustainability is integrated into study programs.

In the next stage, we identified curricula' contribution to sustainability using STAUNCH® assessment criteria (see Table 1). The Sustainability Tool for Auditing University Curricula in Higher Education (STAUNCH) was designed to audit the education for sustainability and global citizenship content of higher education curricula. It must be noted here that in our study, we identified the presence of sustainability-related topics in the syllabuses but did not assess the depth or quality of their integration as in all examined SF and SI courses syllabuses, the sustainability contribution was only mentioned, but there was no further explanation given on how it is addressed.

Table 1. STAUNCH® curricula contribution to sustainable development assessment criteria [1].

Criterion	Specific Description
Economic:	• GNP, Productivity • Resource use, exhaustion (materials, energy, water) • Finances and SD • Production, consumption patterns • Developmental economics
Environmental:	• Policy/Administration • Products and services (inc. transport) • Pollution/Accumulation of toxic waste/Effluents • Biodiversity • Resource efficiency and eco-efficiency • Global warming, Emissions, Acid rain, Climate change • Resources (depletion, conservation) (materials, energy, water) • Desertification, Deforestation, Land use • Ozone depletion • Alternatives
Social:	• Demography, Population • Employment, Unemployment • Poverty • Bribery, Corruption • Equity, Justice • Health • Social cohesion • Education • Diversity • Cultural diversity (own and others) • Labour, Human rights
Cross-cutting Themes:	• People as part of nature/Limits to growth • Systems thinking/Application • Responsibility • Governance • Holistic thinking • Long-term thinking • Communication/ Reporting • SD statement • Disciplinarity • Ethics/Philosophy

[1] Source: [48].

In the final stage, we detected locations in the courses' syllabuses where the information on sustainability was mentioned. We considered four locations: course description, content, teaching objectives, and learning outcomes.

4. Results

We analysed the mechanical engineering programs offered by three of the top technical universities in Europe, as per the QS World University 2022 ranking. In this section, we present the universities' dedication to sustainability, followed by a comprehensive quantitative and qualitative assessment of their mechanical engineering programs.

4.1. Universities' Commitment to Sustainability

4.1.1. The Politecnico di Milano

The Politecnico di Milano has a strong and comprehensive commitment to sustainability, which is evident in its core values, strategic plan, and institutional initiatives. The university recognises its impact on society and the environment through education, research, and outreach activities, and thus places a high value on responsibility, integrity, respect, professionalism, fairness, trust, and transparency. In its Strategic Plan 2023/25, the Politecnico di Milano emphasises sustainable growth as a core principle. The university aims to significantly impact the country's social and cultural progress while reinforcing the ethical dimension as the foundation of its work. Sustainability is seen as a unifying perspective that extends to all academic domains: research, teaching, and social responsibility. Teaching at the Politecnico di Milano focuses on educating students to address global challenges critically and offers them tools to foster equal opportunities in a supportive learning environment. In terms of research, the university emphasises ethical considerations in scientific and technological development, fosters interdisciplinary partnerships, and focuses on talent development and career support for young researchers. The Politecnico di Milano's commitment to social responsibility involves actions and projects that respond to the needs of the local and international community. The university takes a proactive approach to sustainable development, and its efforts are aligned with the 17 Sustainable Development Goals (SDGs) of the UN 2030 Agenda. The university's initiatives include promoting environmental sustainability, responsible research, international cooperation for development, and equal opportunities. The Code of Ethics and Conduct at the Politecnico di Milano reflects the university's strong commitment to responsibility, respect, integrity, professionalism, fairness, trust, and transparency. The code acknowledges the impact of the university's activities on society and the environment and emphasises the pursuit of social, economic, and environmental sustainability. It fosters a culture of responsibility among the university community, including students, staff, and researchers, promoting dignity, equality, and diversity. The code upholds ethical behaviour, independence, and honesty while condemning conflicts of interest and unethical practices. The Politecnico di Milano's Code of Ethics and Conduct sets the foundation for its ethical and sustainable approach to education, research, and service to the community. It should be emphasised that the Politecnico di Milano actively measures and validates the results and effectiveness of its sustainability efforts through various reports and publications, including the SDGs@Polimi reports and the University Environmental Sustainability Report.

Drawing from the details available on the website, the Politecnico di Milano's commitment to sustainability encompasses various aspects of its institutional activities, from teaching and research to community engagement and social impact. The university strives to be a sustainable development role model and contribute to a more equitable, inclusive, and environmentally conscious future.

4.1.2. The Technical University of Munich

The Technical University of Munich (TUM) is strongly committed to sustainability and resilience, reflected in its vision, mission, and core values. TUM aspires to be a leading entrepreneurial university, contributing to global knowledge exchange and shaping the future responsibly with talent and excellence. TUM's Sustainable Futures Strategy 2030 aims to position the university as a sustainable scientific, economic, ecological, and social development driver. The university recognises the interconnectedness of environmental limits, economic resilience, and social justice in pursuing sustainability goals. TUM's sustainability strategy involves engaging all university community members, including students, teaching staff, researchers, and employees, in adopting responsible actions for sustainability in their day-to-day activities. The university employs a participative process to identify action fields, prioritise focus areas, and define concrete measures toward sustainability. Education and lifelong learning play a crucial role in TUM's commitment to sustainability. The university focuses on providing excellent education for responsible talents for change, equipping students and employees with sustainability knowledge and skills to contribute actively to sustainable transformation. TUM creates a sustainable teaching and learning environment and qualifies lecturers through training courses on sustainability in teaching. The university offers a selection of degree programs emphasising sustainability as a core topic. These programs cover various disciplines such as Biotechnology and Sustainability, Agrosystem Sciences, Forest Science and Resource Management, Green Electronics, Ecological Engineering, Politics and Technology, Resource Efficient and Sustainable Building, Responsibility in Science, Engineering, and Technology, Sustainable Resource Management, and Urbanism—Urban and Landscape Studies and Design. Furthermore, TUM collaborates with partner universities in the EuroTech Universities Alliance to develop study programs and continuous learning initiatives for future engineering graduates, aligning them with sustainable development goals. Based on the information presented on TUM's website, we can conclude that the university demonstrates a comprehensive and ambitious approach to sustainability, actively promoting responsibility, environmental consciousness, and societal progress in all aspects of its academic and institutional activities.

4.1.3. The University of Manchester

The University of Manchester is demonstrating a solid commitment to sustainability, particularly in relation to the United Nations' Sustainable Development Goals (SDGs). The university has achieved remarkable recognition in the impact ranking for its performance in meeting the SDGs, securing the top position in the UK for three consecutive years (2019, 2020, and 2021) and even becoming the first UK university to attain the number one position globally among over 1200 universities in 98 countries in 2021. The university's vision revolves around being globally acknowledged for the excellence of its people, research, learning, and innovation, as well as the positive impact it creates for society and the environment. To achieve this vision, the university has laid a strategic plan focusing on three core goals: research and discovery, teaching and learning, and social responsibility. These goals are supported by four key themes: innovation, civic engagement, global influence, and environmental sustainability. Within teaching and learning, the strategic plan for 2021–2025 emphasises incorporating sustainable development education through interdisciplinary approaches. Students are encouraged to learn about the SDGs by identifying modules marked for their sustainable development content and the opportunities offered by the University College for Interdisciplinary Learning (UCIL). Regarding social responsibility, the university has identified five key priorities: social inclusion, prosperous communities, better health, environmental sustainability, and cultural engagement. In line with this commitment, the university has purposefully aligned various aspects of its research, teaching and learning, engagement, and campus operations to support the SDGs. This includes promoting student engagement with the SDGs through multiple programs and initiatives, such as the Stellify program, University College for Interdisciplinary Learning units, the 50,000 Actions platform, the University Living Lab platform, and prospective student course profiles. Furthermore, the university aims to launch a revised set of graduate attributes for undergraduate and postgraduate programs linked to social responsibility and the SDGs by 2022.

Table 2 summarises the commitment to sustainability of the three analysed technical universities.

Based on the information provided and the disclosed commitments on the websites of the Politecnico di Milano, the Technical University of Munich (TUM), and the University of Manchester, it can be observed that the commitment to sustainability across analysed higher education institutions appears to be robust and comprehensive. In every aspect we explored, each institution demonstrates programs and initiatives pertaining to the operationalisation of sustainability. However, it is essential to note that the conclusion drawn about the similarity in the commitment to sustainability among the three higher education institutions (HEIs) is based on the information publicly disclosed by these institutions on their websites. While the disclosed information provides valuable insights into their stated values, strategic plans, and initiatives, it may not fully capture each institution's nuances and real practices.

Table 2. Institutional commitment to sustainability [1].

Aspect	Politecnico di Milano	Technical University of Munich	University of Manchester
Core Values and Strategic Plan	Strong and comprehensive commitment to sustainability; core values include responsibility, integrity, respect, professionalism, fairness, trust, and transparency; Sustainable growth emphasised in the Strategic Plan 2023/25.	Strong commitment to sustainability reflected in vision, mission, and core values; Sustainable Futures Strategy 2030 aims for sustainable scientific, economic, ecological, and social development; interconnectedness of environmental limits, economic resilience, and social justice recognised.	Strong commitment to sustainability demonstrated in vision and strategic plan; emphasis on research and discovery, teaching and learning, and social responsibility; aligned with the UN SDGs; strategic goals supported by innovation, civic engagement, global influence, and environmental sustainability.
Teaching and Learning	Focus on educating students to address global challenges critically; tools for fostering equal opportunities; interdisciplinary partnerships in research; ethical considerations in scientific and technological development.	Strong focus on providing an excellent education for responsible talents; sustainability knowledge and skills integrated into teaching; sustainable teaching and learning environment; diverse degree programs covering various sustainability topics; collaboration with partner universities for sustainable study programs.	Incorporation of sustainable development education through interdisciplinary approaches; identification of modules with sustainable development content; commitment to launching a revised set of graduate attributes linked to social responsibility and SDGs.
Research and Innovation	Emphasis on ethical considerations in research; interdisciplinary partnerships; focus on talent development and career support for young researchers; alignment with UN SDGs; proactive approach to sustainable development.	Active engagement of the university community in adopting responsible actions; participative process for defining measures towards sustainability; collaboration with EuroTech Universities Alliance for sustainable study programs; alignment with sustainable development goals.	Strong performance in meeting UN SDGs; research, teaching, engagement, and campus operations aligned with the SDGs; various programs and initiatives to promote student engagement with the SDGs; revised graduate attributes linked to social responsibility and SDGs.
Social Responsibility and Engagement	A proactive approach to social responsibility; actions and projects responding to local and international community needs; alignment with UN SDGs; Code of Ethics and Conduct fostering a culture of accountability, dignity, equality, and diversity.	Engagement of all university community members in responsible actions; emphasis on social inclusion, prosperous communities, better health, environmental sustainability, and cultural engagement; various programs and platforms promoting student engagement with the SDGs.	Top-ranking performance in meeting UN SDGs; strategic goals supported by civic engagement, global influence, and environmental sustainability; various programs and initiatives to engage students with the SDGs.
Measurement and Validation	Actively measures and validates sustainability efforts through reports and publications, including SDGs@Polimi reports and the University Environmental Sustainability Report.	Utilises a participative process to identify action fields and define concrete measures towards sustainability; ongoing collaboration with partner universities for continuous learning initiatives; alignment with EuroTech Universities Alliance.	Recognised globally for performance in meeting SDGs; alignment with SDGs integrated into various programs and initiatives; commitment to launch revised graduate attributes linked to SDGs by 2022.

[1] Own elaboration based on the information available on the universities' websites.

4.2. Analysis of the Mechanical Engineering Programs

4.2.1. The Politecnico di Milano

The Master's in Mechanical Engineering at the Politecnico di Milano is a two-year programme (120 ECTS credits) and offers nine programs: Mobility Engineering, Machine Tools Engineering, Ground Vehicles, Advanced Materials and Manufacturing, Advanced Mechanical Design, Internal Combustion Engines and Turbomachinery, Mechatronics and Robotics, Virtual Prototyping Campus, Production Systems. The quantitative analysis of sustainability integration into the Master's programs in Mechanical Engineering at the

Politecnico di Milano indicates that the programs vary in their emphasis on sustainability (see Table 3). The courses of the Group OPEN are updated every year before the study plan presentation. Only one course can be selected by the Master's students from the Open Group.

Table 3. Quantitative characteristics of sustainability integration into mechanical engineering program at the Politecnico di Milano.

Mechanical Engineering Programmes (Politecnico di Milano)	Number of Sustainability-Focused Courses SF	Number of Courses that Include Sustainability SI	SF + SI	Total Number of Courses Offered in the Program
Mobility Engineering	1	3	4	11
Machine Tools Engineering	0	1	1	12
Ground Vehicles	0	5	5	28
Advanced Materials and Manufacturing	2	3	5	13
Advanced Mechanical Design	0	2	2	20
Internal Combustion Engines and Turbomachinery	1	4	5	23
Mechatronics and Robotics	0	6	6	18
Virtual Prototyping	0	2	2	13
Production Systems	1	2	3	10
Courses of the Group OPEN	3	2	5	13

Some programs have dedicated sustainability-focused courses (Mobility Engineering, Advanced Materials and Manufacturing, Internal Combustion Engines and Turbomachinery, and Production Systems), while others incorporate sustainability elements into existing courses. The positive sign of redefining mechanical engineering education at Politecnico di Milano is that in all offered programs there are offered courses that include sustainability to some extent. Five out of nine programs stand out in terms of the number of courses that change the traditional perception of mechanical engineering and offer sustainability-focused courses as well as courses that include sustainability: Mobility Engineering, Advanced Materials and Manufacturing, Internal Combustion Engines and Turbomachinery, Production Systems. These programs exhibit a strong emphasis on sustainability integration. The courses of the Group OPEN are elective and also emphasise sustainability challenges, where nearly 40% of offered courses include sustainability or are sustainability-focused.

Table A1 (see Appendix A) presents the analysis results regarding: (a) the way sustainability-related content is integrated into mechanical engineering curricula, (b) the sustainability-related topics are integrated into the curricula, and (c) the location of the sustainability-related topics in the courses' syllabuses of the Politecnico di Milano.

The analysis results indicate that sustainability-related content is integrated into mechanical engineering curricula at the Politecnico di Milano through dedicated sustainability-focused courses (SF) and courses that include sustainability aspects (SI). Table A1 shows that some programs have specific courses solely dedicated to sustainability (SF), while others incorporate sustainability elements within existing courses (SI). The integration is evident in various programs, such as "Mobility Engineering", "Advanced Materials and Manufacturing", "Mechatronics and Robotics", and "Production Systems". These sustainability-related courses cover cross-cutting themes, environmental considerations, economic aspects, and social implications, highlighting the multidimensional approach taken to incorporate sustainability in mechanical engineering education. The curricula demonstrate a well-rounded approach to sustainability by addressing multiple dimensions of sustainability-related challenges.

Based on the available data, we can infer that sustainability-related topics are likely integrated into various parts of the syllabuses, such as course content, course descriptions, learning outcomes, and teaching objectives. For example, in the "Virtual Prototyping" program courses like "Methods and Tools for Systematic Innovation" and "Design Methods" mention cross-cutting, environmental, and economic themes in their course descriptions, learning outcomes, and teaching objectives. In the "Ground Vehicles" program, the course "Design Methods" includes cross-cutting, environmental, and economic aspects, possibly mentioned in different syllabus sections. The integration of sustainability-related topics throughout the syllabuses reflects the comprehensive approach taken by the university to infuse sustainability principles across mechanical engineering courses.

4.2.2. The Technical University of Munich

The TUM offers a two-year program on Mechanical Engineering, in particular, devoted to eight possibilities: "Mechanical Engineering", "Vehicle and engine technology", "Energy and process engineering", "Development and construction", "Aerospace, Mechatronics and Information Technology", "Mechanical Engineering and Management", "Production and Logistics". Students have two years to obtain an obligatory number of 120 ECTS points regarding their profile and interests. However, they need to learn certain basic areas of expertise.

Based on the documents provided by the Technical University of Munich, it is impossible to select the specific subjects to be taken by the students in their chosen year of study, as the students are free to compose the timing of the courses. It is only known when they take place—either in the summer semester or in the winter semester. Students are obliged to collect a certain number of ECTS credits over the entire study cycle without being divided into years of study.

The student can choose from compulsory technical subjects and additional content over the entire study cycle. Table A2 (see Appendix B) presents the analysis results regarding (a) the way sustainability-related content is integrated into mechanical engineering curricula, (b) the sustainability-related topics are integrated into the curricula, and (c) the location of the sustainability-related topics in the courses' syllabuses of the University of Munich.

Based on the results, it can be concluded that the courses' syllabuses present some references to sustainability and one of the offered courses can be categorised as sustainability-focused. Any elective supplementary courses and elective practical courses do not include sustainability issues. On the other hand, the content offered in terms of technical preparation for mechanical engineering is extensive. At the master's level, the student has to demonstrate extensive competence in theory and its applications in mechanics, mechanical engineering, production technology, or modern solutions used in technology.

It should be emphasised that, within the two courses offered on the social skills courses in the mechanical engineering programme, each includes social and cross-cutting themes in the syllabuses, which are mentioned in three places: course description, learning outcomes, and teaching objectives. Within the required Elective Master courses at the Technical University in Munich, 12 courses that include sustainability out of the 55 offered (see Table 4) were identified. Only one course was categorised as sustainability-focused: "Environmental and Biochemical Engineering".

The analysis revealed that in the master mechanical engineering programme, in 15 analysed courses, all four sustainability themes (social, environmental, economic, cross-cutting) appear in the subject syllabuses, but to a different extent. Referring to location of them, these are most often mentioned in learning outcomes or much less often in course descriptions.

Table 4. Quantitative characteristics of sustainability integration into the mechanical engineering programme at the Technical University of Munich.

Mechanical Engineering Programmes (Technical University of Munich)	Number of Sustainability-Focused Courses SF	Number of Courses that Include Sustainability SI	Total Number of Courses Offered in the Program
Social Skills Modules	0	2	2
Required Elective Master Modules	1	12	55
Elective Supplementary Courses	0	0	6
Elective Practical Courses	0	0	6

4.2.3. The University of Manchester

The University of Manchester offers eight programs. From the description of the content of the programs on offer, it is apparent that they are all modern in form and contain content that reflects the market demands of contemporary engineering. The duration of the program is not mentioned on the website. However, according to the European Credit Transfer and Accumulation System (ECTS), a Master's degree typically equates to 90 or 120 ECTS credits.

After reviewing the content of the courses, it should be noted that direct references to sustainability are found in two programs—Reliability Engineering and Asset Management, and the other is Robotics. Among the programs offered, it deserves a special mention the one devoted entirely to renewable energy and sustainable manufacturing technologies—"Renewable Energy and Clean Technology", which aligns with the UN Sustainable Development Goals: Goal 7: Affordable and clean energy, Goal 9: Industry, innovation, and infrastructure, Goal 11: Sustainable cities and communities, Goal 12: Responsible consumption and production, Goal 13: Climate action.

Table A3 (see Appendix C) presents the detailed analysis results regarding (a) the way sustainability-related content is integrated into mechanical engineering curricula, (b) the sustainability-related topics integrated into the curricula and (c) the location of the sustainability-related topics in the courses' syllabuses of the University of Manchester.

The study revealed that the evaluated mechanical engineering master programs at the University of Manchester include sustainability focus (SF) courses, sustainability inclusive (SI) courses and courses where there is no evidence that the content is related to sustainability themes. The study identified different approaches to integrating sustainability into mechanical engineering master's programs. In one case, the study distinguished the inclusion of both SI and SF courses in the "Renewable Energy and Clean Technology" program, in others, only SI courses. The analysis in terms of the number of offered SI and SF courses also showed considerable differences among analysed programs (see Table 5). Out of the six programs offered, only three offer courses that include sustainability: "Reliability Engineering and Asset Management", "Robotics" and "Renewable Energy and Clean Technology" programs. Regarding sustainability-focused courses, they appear in only one program—"Renewable Energy and Clean Technology", which is a program devoted entirely to renewable energy and sustainable manufacturing technologies.

Some courses address cross-cutting themes, meaning they may encompass sustainability principles that can be applied across various engineering disciplines. Examples of cross-cutting themes include courses: "Design for Reliability & Asset Management" and "Techniques for Research and Industry". The scope of incorporating sustainability into the courses varies, in some cases, it is comprehensively included and visible in all analysed elements: content, course description, learning outcomes, teaching objectives, and in some cases only mentioned as in the courses: Robotics Systems or Smart Grids and Sustainable Electricity Systems (see Table A3). Master's program "Renewable Energy and Clean Technology" provides a comprehensive and interdisciplinary approach to renewable energy and clean technology, considering economic, environmental, and social aspects while exploring different sustainable energy sources and their applications.

Table 5. Quantitative characteristics of sustainability integration into mechanical engineering programs at the University of Manchester.

Mechanical Engineering Programs (University of Manchester)	Number of Sustainability-Focused Courses SF	Number of Courses that Include Sustainability SI	Total Number of Courses Offered in the Program
Advanced Manufacturing Technology and Systems Management	0	0	9
Renewable Energy and Clean Technology	6	1	9
Mechanical Engineering Design	0	0	9
Reliability Engineering and Asset Management	0	3	9
Robotics	0	1	7
Thermal Power and Fluid Engineering	0	0	10

5. Discussion and Conclusions

The paper outlines four research questions central to the empirical part of the study. These inquiries, on the one hand, seek to explore the commitment to sustainability of selected top technical universities in Europe and, on the other hand, to understand how sustainability-related content is integrated into Masters' mechanical engineering programs, to identify the specific sustainability-related topics covered and determine their placement within the course syllabuses.

Although the three top technical universities in Europe demonstrate a comprehensive commitment to sustainability, in every aspect we explored, the empirical analysis highlighted the diverse approaches they have adopted to integrate sustainability into mechanical engineering master programs. We found similarities and differences in the sustainability integration among the three institutions. All universities demonstrate a commitment to environmental sustainability in their Mechanical Engineering programs, as evidenced by courses such as "Electric System for Transportation", "Environmental and Biochemical Engineering", and "Solar Energy Technologies". Furthermore, each institution adopts a holistic approach by integrating cross-cutting themes. This involves addressing multiple sustainability aspects within a single course, as seen in examples such as "Design Methods" at Politecnico di Milano, "Design for Reliability & Asset Management" at TUM, and "Understanding Energy as a 'system' driving modern society" at the University of Manchester. Regarding differences, the University of Manchester places a relatively more robust emphasis on social sustainability. Courses like "Understanding Energy as a 'system' driving modern society" and "Robotic Systems" highlight a pronounced focus on social themes. While Politecnico di Milano and TUM also address social aspects, the emphasis is more prominent at the University of Manchester. Moreover, TUM explicitly integrates economic dimensions into its courses, such as "Safety, Legislation & Cost Effectiveness" and "Asset Management Strategy & Organisation". In contrast, while economic considerations are present in the offerings of Politecnico di Milano and the University of Manchester, they are not explicitly highlighted to the same extent as at TUM.

Certain emphasis tracks, particularly those related to mobility engineering, advanced materials, renewable energy, and reliability engineering, stand out as more inclusive of sustainability content across economic, environmental, and social dimensions. Politecnico di Milano's Mobility Engineering Program features courses like "Electric System for Transportation", "Energy and Emissions in Transportation Systems", and "Rail Vehicle Dynamics and Train-Track Interaction", demonstrating a significant emphasis on sustainability, particularly in environmental and cross-cutting themes. In the Advanced Materials and Manufacturing Program, courses such as "Materials Engineering Recycling and Environmental Impact" and "De-Manufacturing" underscore a strong commitment to sustainability, covering cross-cutting themes, environmental considerations, and economic aspects. Technical University of Munich's (TUM) Master's Program in Mechanical Engineering includes courses like "Environmental and Biochemical Engineering", explicitly addressing environmental sustainability. Additionally, the emphasis on "Human Reliability" highlights the inclusion of social and economic aspects. At the University of Manchester, the Reliability Engineering and Asset Management program, featuring courses like "Design for Reliability & Asset Management" and "Asset Management Strategy & Organisation", indicates a notable emphasis on economic and cross-cutting themes, demonstrating a practical application of sustainability in asset management. Similarly, in the Renewable Energy and Clean Technology program at the University of Manchester, courses like "Smart Grids & Sustainable Electricity Systems", "Interfacing clean energy systems", and "Understanding Energy as a 'system' driving modern society" demonstrate a robust integration of sustainability across economic, environmental, and social dimensions.

While common sustainability themes may be addressed across institutions, the specific emphasis areas seem unique to each program. Politecnico di Milano and TUM have specific programs with distinct focuses, such as mobility engineering and environmental and biochemical engineering, respectively. The University of Manchester's emphasis areas include reliability engineering and asset management, as well as renewable energy and clean technology. In summary, the emphasis areas offered at each institution appear to be unique, showcasing a diverse range of sustainability-related topics within their Mechanical Engineering programs.

The results of our study reveal that while progress has been made in incorporating sustainability into higher education, there is room for improvement in achieving a more holistic and systematic approach to integrating sustainability principles throughout engineering programs. Not every Master's student, upon completion of a mechanical engineering degree from the three institutions, was exposed to sustainability topics in one or more mandatory courses. Based on the collected data, we can state that this is true for mechanical engineering Master's students from the University of Manchester (three tracks had no sustainability-focused courses, nor did they include sustainability-related courses).

Further steps should be taken to enhance the integration of sustainability into the curricula by offering both sustainability-related and sustainability-focused courses to provide students with a comprehensive understanding of sustainable engineering practices and their relevance in various sectors. The importance of transdisciplinary thinking in sustainability education should be emphasised [46]. Mechanical engineering curricula should go beyond the traditional focus on technology and environmental issues and include economic and social factors in sustainability considerations. This will help mechanical engineers develop a broader perspective on sustainability challenges related to environmental, economic, and social sustainability and contribute more effectively to addressing them.

This study has some limitations. The research focused on only three top technical universities in Europe as the study faced limitations in accessing complete and up-to-date information from all universities. Some universities did not disclose their program syllabuses, limiting the data available for analysis. The findings might not be generalisable to other institutions with different approaches to sustainability integration. Still, this research is a case study to investigate the approach of the best technical universities in the EU. The second limitation is the subjective nature of content analysis. Content analysis involves subjective judgment in categorising courses as sustainability-focused (SF), sustainability-inclusive (SI), or unrelated to sustainability. Different researchers might interpret course materials differently, leading to potential inconsistencies in categorisations.

The authors see some opportunities for future research. The first one is to expand the scope of the study to include a larger number of universities from different regions in Europe, which would provide a more comprehensive understanding of how sustainability is integrated into mechanical engineering programs across the continent. The next possible direction is to employ a mixed-methods approach, combining content analysis with surveys or interviews, which could offer a more holistic understanding of universities' sustainability initiatives, challenges, and plans. Future research could also delve deeper into assessing sustainability-focused and inclusive courses' actual contribution to mechanical engineering programs. This could involve evaluating the effectiveness of pedagogical approaches, student learning outcomes, and graduates' real-world applications of sustainability principles.

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Appendix A

Table A1. Analysis of the syllabuses content from the Politecnico di Milano.

Name of the Program and the Courses Politecnico di Milano	SF/SI	Sustainability-Related Theme	Content (Even if One of the Topics Cover Sustainability-Related Theme)	Course Description	Learning Outcomes	Teaching Objectives
Mobility engineering program						
Ethics For Transportations	SF	Cross-cutting themes; social	x	x	x	x
Electric System for Transportation	SI	Environmental		x		
Energy And Emissions in Transportation Systems	SI	Cross-cutting themes, environmental		x	x	
Rail Vehicle Dynamics and Train-Track Interaction	SI	Environmental	x			
Machine tools engineering program						
Rail Vehicle Dynamics and Train-Track Interaction	SI	Environmental	x			

Table A1. *Cont.*

Name of the Program and the Courses Politecnico di Milano	SF/SI	Sustainability-Related Theme	Content (Even if One of the Topics Cover Sustainability-Related Theme)	Course Description	Learning Outcomes	Teaching Objectives
Ground vehicles program						
Rail Vehicle Dynamics and Train-Track Interaction	SI	Environmental	x			
Design Methods	SI	Cross-cutting, environmental, economic	x			
Internal Combustion Engines	SI	Environmental			x	
Electric System for Transportation C	SI	Environmental		x		
Methods And Tools for Systematic Innovation	SI	Environmental, cross-cutting themes		x	x	
Advanced materials and manufacturing program						
Materials Engineering Recycling and Environmental Impact	SF	Cross-cutting themes, environmental, economic		x	x	
De-Manufacturing	SF	Cross-cutting themes, environmental, economic		x	x	
Advanced Manufacturing Processes	SI	Environmental, cross-cutting themes			x	
Innovations In Metallurgical Plants and Processes	SI	Economic, environmental		x	x	
Advanced Manufacturing Processes Lab	SI	Environmental, cross-cutting themes			x	
Advanced mechanical design program						
Methods And Tools for Systematic Innovation	SI	Cross-cutting themes, environmental		x	x	
Methods For Advanced Mechanical Design	SI	Cross-cutting themes, environmental	x		x	

Table A1. *Cont.*

Name of the Program and the Courses Politecnico di Milano	SF/SI	Sustainability-Related Theme	Content (Even if One of the Topics Cover Sustainability-Related Theme)	Course Description	Learning Outcomes	Teaching Objectives
Internal combustion engines and turbomachinery program						
Power Production from Renewable Energy	SF	Cross-cutting, environmental, economic		x	x	
Design Methods	SI	Cross-cutting, environmental, economic	x			
Electric System for Transportation	SI	environmental		x		
Methods and Tools for Systematic Innovation	SI	Cross-cutting, environmental,	x	x	x	
Design of Fluid Machines for Clean Power Generation	SI	Environmental		x		
Mechatronics and robotics program						
The theme self-mapped by the teacher in reference to SDG's						
Mechatronic Systems and Laboratory	SI	SDG9				
Automatic Control	SI	SDG9				
Hybrid and Electric Vehicle	SI	SDG12; SDG13				
Rail Vehicle Dynamics and Train-Track Interaction	SI	Environmental	x			
Methods and Tools for Systematic Innovation	SI	SDG9, SDG12, SDG13				
Autonomous Vehicles	SI	SDG9, SDG11				
Virtual prototyping program						
Methods and Tools for Systematic Innovation	SI	Cross-cutting, environmental,	x	x	x	
Design Methods	SI	Cross-cutting, environmental, economic	x			
Production systems program						
Advanced and Sustainable Manufacturing	SF	Cross-cutting, environmental, social, economic		x		
Industrial Risk Management	SI	Cross-cutting, environmental,		x		
Asset Life Cycle Management	SI	Cross-cutting themes		x		

Appendix B

Table A2. Analysis of the syllabuses content from the Technical University of Munich.

Name of the Course Technical University of Munich	SF/SI	Sustainability-Related Theme	Content (even if One of the Topics Cover Sustainability-Related Theme)	Course Description	Learning Outcomes	Teaching Objectives
Master's Program Mechanical Engineering						
Social Skill Courses						
Master Soft Skill Workshops	SI	Social/Cross-cutting themes		x	x	x
Soft Skill Training in Project Cooperations	SI	Social/Cross-cutting themes		x	x	x
Required Elective Master Courses						
Methods of Product Development	SI	Cross-cutting themes			x	x
Heat and Mass Transfer	SI	Environmental			x	x
System Engineering for Vehicle Drive Lines	SI	Cross-cutting themes			x	
Biocompatible Materials 2 and Interdisciplinary Seminar	SI	Social/Cross-cutting themes			x	
Power Plant Components	SI	Environmental		x	x	
Engine Mechanics	SI	Environmental			x	
Material Flow Systems	SI	Environmental			x	
Product Ergonomics	SI	Social/Cross-cutting themes			x	
Combustion	SI	Environmental		x	x	
Thermodynamics of Internal Combustion Engines and Combustion Processes	SI	Cross-cutting themes			x	
Human Reliability	SI	Social/Economic/Cross-cutting themes		x	x	
Modeling, Control and Design of Wind Energy Systems	SI	Environmental		x		
Environmental and Biochemical Engineering	SF	Environmental	x	x	x	x

Appendix C

Table A3. Analysis of the syllabuses content from the University of Manchester.

Name of the Program and the Courses University of Manchester	SF/SI	Sustainability-Related Theme	Content (even if One of the Topics Cover Sustainability-Related Theme)	Course Description	Learning Outcomes	Teaching Objectives
Reliability Engineering and Asset Management						
Asset Management Strategy and Organisation	SI	Economic	x	x	x	
Safety, Legislation and Cost Effectiveness	SI	Economic, environmental	x	x	x	
Design for Reliability and Asset Management	SI	Cross-cutting	x	x	x	
Robotics						
Robotic Systems	SI	Cross-cutting			x	
Renewable Energy and Clean Technology						
Smart Grids & Sustainable Electricity Systems	SF	Economic, environmental	x			
Interfacing clean energy systems	SF	Environmental	x			
Understanding Energy as a 'system' driving modern society	SF	Economic, environmental, social	x	x	x	x
Solar Energy Technologies	SF	Environmental	x		x	x
Zero Carbon Built Infrastructure	SF	Environmental, Cross-cutting	x	x	x	x
Marine Energy: Wind, Wave and Tidal	SF	Environmental	x	x	x	x
Techniques for Research and Industry	SI	Cross-cutting	x	x	x	x

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