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Sustainable Technologies Supported by Project-Based Learning in the Education of Engineers: A Case Study from Poland

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Abstract: The aim of the article is to examine technological innovations developed by engineers as part of Project-Based Learning at one of the Polish technical universities. We examined whether the innovations being developed meet the goals of sustainable development and whether they provide the basis for the introduction of sustainable business models. We analyzed reports from 49 projects implemented in the years 2018–2020 in which 146 scientists, 282 students of the Silesian University of Technology, and 126 experts from the university's business environment were involved. We performed the analysis using content analysis and visualization techniques. The results show that the studied innovations implement the goals of sustainable development and most of them may become the basis of sustainable business models. The most frequently pursued goals are Industry, Innovation, and Infrastructure and Good Health and Well-Being. Most of the studied innovations can become the basis of the archetype of a sustainable business model called "maximize material and energy efficacy". We also provide the characteristics of projects that implement the diagnosed goals of sustainable development.

Keywords: sustainable technologies; sustainable development; SD; sustainable business models; SBM; SBM archetypes; sustainable innovation; sustainable development goals; SDGs

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Citation: Podgórska, M.; Zdonek, I. Sustainable Technologies Supported by Project-Based Learning in the Education of Engineers: A Case Study from Poland. *Energies* **2022**, *15*, 278. https://doi.org/10.3390/en15010278

Academic Editor: Dalia Štreimikienė

Received: 25 November 2021
Accepted: 28 December 2021
Published: 1 January 2022

1. Introduction

The research described in this article was founded on issues related to sustainable technologies, which are the basis for creating sustainable business models. Sustainable development (SD) issues affect all organizational aspects of human life, from an economic, social, political, and environmental point of view. This means a change in all behavioral models and the need to break the assumption that all human activities are based on the paradigm of unlimited resources and the world's unlimited ability to regenerate. It is also related to the introduction of new technology, which, together with culture and economy, will have to provide tools and opportunities to build new solutions towards the concept of sustainable development. In conclusion, this new technology, these new business models, and new lifestyle models will be the milestones of a new sustainable world [1]. This is also confirmed by other researchers who indicate that in order to achieve SD, drastic sociological changes (e.g., [2,3]) are needed, and the rising of emerging economies, growing global population, and environmental burden require innovation based on all three pillars of SD [4]. In this context, [5,6] indicate that the current progress in sustainable development requires a shift from homogeneous systems of "doing things better" to holistic systems of "doing better things". It is no longer enough just to improve existing operations or develop incremental innovations based on existing know-how or technology [7,8]. Instead, radical innovations are needed that typically result from paradigm shifts with high sustainability potential [9,10] and development of new business models that will help to create and implement innovative business processes for SD by, for example, adopting a circular economy strategy (CE) [11], introducing integrated water resource management (IWRM) [12,13], implementing technologies based on eco-innovations [14], or technologies leading to sustainable production [15].

Sustainable development issues are addressed by various entities at international, national, and local levels. The implementation of SD is not a simple task and requires the contribution of various entities that implement or support projects aimed at achieving the SD goals. One of such entities are universities, which make a significant contribution to sustainable development. However, despite the influence of universities on development towards sustainable development as indicated in the literature (e.g., [16,17]), there is limited research that would present the role of higher education institutions as initiators of projects supporting the creation of sustainable business models. This is an indication that the links between the sustainable development paradigm and innovation in higher education are underdeveloped. For example, some researchers have discussed the students' perception of SD (e.g., [18,19]), and their level of education in this area (e.g., [20]), while others discussed teachers' contribution to achieving sustainable development [21] or the implementation of sustainable development in higher education [16,22,23]. However, the analysis of these studies shows that they do not capture the possibility of using a project-oriented approach in engineering education to create sustainable business models, and as they emphasize in their research [24], there is a need to apply design thinking to innovation in sustainable business models.

Therefore, the aim of the article is to broaden the knowledge on the impact of the results of innovative projects implemented at universities on sustainable development. One of these initiatives is the project "Silesian University of Technology as a Centre for Modern Education based on research and innovation" co-financed by the EU under the European Social Fund, in which the authors of this study were involved. As part of one of the tasks of the aforementioned project, innovative projects of engineers implemented by the Project-Based Learning (PBL) method are implemented by way of a competition. Thus, we set a few specific goals for our article. Firstly, we determined what goals of sustainable development are implemented in the researched projects. Secondly, we defined which specialists and with which technologies achieve these goals. Finally, we established what archetypes of sustainable business models can arise from the innovations proposed in the studied projects. We pursue all of these goals using qualitative content analysis of project documentation and visualization techniques.

The paper is organized as follows. Section 2 presents literature review and research questions development. In this section sustainable development goals and archetypes of sustainable business models are characterized. Section 3 describes the methodology of the empirical research. Results are reported in Section 4. Discussion theoretical and practical implications, limitations, and further studies are presented in Section 5.

2. Literature Review

2.1. Sustainable Development Goals

Sustainable development (SD), in addition to a wide range of environmental problems, deals with diverse and complex challenges that change with human communities and natural ecosystems around the world [25]. It is defined as "social learning and control processes" [26] in which sustainable development acts as a discourse or process of achieving SD goals [27,28]. The Sustainable Development Goals (SDGs) were set at the UN Summit on Sustainable Development in September 2015. They are contained in Transforming Our World: The 2030 Agenda for Sustainable Development [29], which describes 17 goals for global challenges critical to human survival and with 169 related targets. The defined SDGs cover three dimensions: sustainable economic development, aimed at securing liquidity and ensuring profit [30] of sustainable social development, which contributes to the development of human and social capital; and environmental sustainability, which relates to the consumption of those resources that can be recreated from living and inanimate things [31,32]. SDGs are used in areas such as education, health, climate change and environmental protection, as well as social protection and employment opportunities. SDGs are not independent but interrelated, and represent the master plan for achieving a sustainable future for all [33]. The SDGs with their description and main tasks are presented in Table 1.

Table 1. SDGs of Agenda 2030.

Category	No.	SDGs of Agenda 2030	Description	Main Actions
Social	2	Zero hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Investments in agriculture as a key element for increasing production capacity Introduce sustainable food production systems to reduce the risk of hunger
	3	Good health and well-being	Ensure healthy lives and promote well-being for all at all ages	Continue to work hard to tackle the prevalence of many diseases and emerging health threats Ensure more effective financing of health systems, improve sanitation and hygiene, access to doctors and reduce environmental pollution
	4	Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Ensuring quality education involves creating educational scholarship programs, workshops for teachers, building schools, and improving access to water and electricity in schools
	5	Gender equality	Achieve gender equality and empower all women and girls	Ensure that women and girls have equal access to education, health care, and decent work, and participate in political and economic decision-making Implement the new legal framework on equality in the workplace and combat harmful practices against women
	10	Reduce inequalities	Reduce inequality within and among countries	Mainstream the needs of disadvantaged and marginalized groups as a general principle in policies seeking to reduce inequalities. Extend duty-free treatment and support exports from developing countries and increase the voting system for developing countries in the International Monetary Fund Technological innovation
Economic	9	Industry, innovation, and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	Greater investment in highly advanced technologies to increase the efficiency of manufacturing. Development of mobile phone services that increase people-to-people contacts

Table 1. *Cont.*

Category	No.	SDGs of Agenda 2030	Description	Main Actions
Environmental	13	Climate and action	Take urgent action to combat climate change and its impacts	Strengthening global action to contain climate change
	14	Life below water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	Adequate management and financing of marine protected areas. Introduce regulations to reduce overfishing, pollution of the marine environment, and ocean acidification
	15	Life below land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Better forest management and combating desertification
Socio-economic	1	No poverty	End poverty in all its forms everywhere	Implement social protection systems to mitigate the effects of natural disasters and help vulnerable countries Help the economy of countries prone to natural disasters and end extreme poverty in the poorest regions
	8	Decent work and economic growth	Promote sustained, inclusive, and sustainable economic growth, full productive employment, and decent work for all	Increasing access to financial services so as to manage income properly, accumulate wealth, and make effective investments Increase funds for the development of trade, banking, and agricultural infrastructure
Economic-environmental	7	Affordable and clean energy	Ensure access to affordable, reliable, sustainable, and modern energy for all	Increase access to clean fuels and technologies, as well as the use of renewable energy sources in buildings, transport, and industry Increase public and private energy investment More emphasis on the regulatory framework and innovative business models in transforming the world's energy systems
Socio-environmental	6	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all	Increase investment in management of freshwater ecosystems and sanitation at the local level
Encompassing all three dimensions	11	Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient, and sustainable	Improve resource efficiency Strive to reduce pollution and prevent poverty Urban development and counteracting rapid urbanization
	12	Responsible production and consumption	Ensure sustainable consumption and production patterns	Conduct educational and other activities for consumers to raise their awareness of sustainable consumption and related lifestyle through (e.g., conducting information campaigns on product standards and labeling, engaging consumers in public procurement issues)

Table 1. *Cont.*

Category	No.	SDGs of Agenda 2030	Description	Main Actions
Governance/ Political will	16	Peace, justice, and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all, and build effective, accountable, and inclusive institutions at all levels	Implement effective and more transparent legislation and draw up comprehensive and realistic state budgets Birth registration and creation of more independent national human rights institutions
	17	Partnership for the goals	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	Long-term investments, including foreign direct investment Development of the public sector Reconstruction of the system of monitoring, review, and regulation as well as construction of incentives stimulating investments Strengthen the national supervisory mechanisms and the supervisory function of the legislature

Source: Based on [34] ([29]).

The achievement of the SDGs depends on the country's performance against the SDGs [35]; therefore, it is necessary to monitor the various socio-ecological indicators that support these objectives [36,37]. In total, 231 unique socio-ecological indicators were used to monitor progress towards these targets and goals [38].

The 2030 Agenda and its 17 Sustainable Development Goals challenge the global community, which must unite more than ever to act globally. This is also emphasized by Guterres [39], who points out that in order to implement SDGs, and then to analyze the degree of their implementation, it is not only necessary to involve governments but all, i.e., the private sector, civil society, and every human being. He adds that despite the progress made in the first stage of Agenda 2030 implementation, the achievement of the goals is not progressing at the required pace and demands more ambitious actions and joint focus that will allow the achievement of the goals in the coming years and enable the achievement of sustainable and inclusive development.

The Sustainable Development Goals go beyond traditional linear development relationships by adopting an inclusive approach that promotes interconnectedness, partnerships, and focuses on complex interactions within and between development goals [40]. This is also underlined by the UN [41], stating that the integrated nature of the SDGs is important and should be taken into account in order to achieve them. Getting closer to achieving a goal can have a negative or positive effect on other goals. The existence of these relationships is the main reason the SDGs are such a complex system. While these complexities present some difficulties, they can actually be beneficial as well [42]. Breuer, Janetschek and Malerba [43] emphasize in this context that maximizing synergies between goals can accelerate their implementation. Given that all SDGs are synergistic, but not necessarily at an equal level [44], identifying those levels and improving goals that have a positive impact on other goals provides more detailed insight into the allocation of resources, thus enabling the achievement of goals to be maximized [42].

In recent years, SD has become widely considered in literature and practice in terms of the impact of higher education on its development [45–47]. For example, analyses have focused on providing education in the field of SD to future generations of engineers [48], integrating SD into the system elements of higher education institutions [49] or conducting case studies on specific universities solutions in the field of SD and their impact on society [50], economy [51], or natural environment [52]. As indicated by researchers (e.g., [53,54]) there has also been significant progress in incorporating SD into the engineering curricula. Enterprises more and more often incorporate SD into their strategies and business plans, and therefore need specialists who have been educated in this subject [54]. Therefore, universities have the task of enabling students to develop the skills of understanding the need for SD, its goals, and acting in accordance with them, by taking into account social, environmental, and economic considerations in making decisions [49,55]. Universities also face the challenge of providing students with the opportunity to translate the knowledge from education for SD into systemic critical thinking and actions [56]. However, as [57] emphasizes incorporation of SD into curricula requires systemic thinking and interdisciplinary approaches and as pointed out by [58] requires pedagogical innovations that provide experimental, interactive, real-world, and transformative learning.

The goals of sustainable development presented by the UN (2015) and the education of engineers in accordance with the concept of Project-Based Learning (PBL) inspired us to pose the following research questions:

Research question 1: What Sustainable Development Goals are considered in PBL?
Research question 2: Which specialists are interested in each of the Sustainable Development Goals?
Research question 3: What are the characteristic technological terms of individual projects in relation to the goal pursued?

2.2. Sustainable Business Models

A conceptual tool helping to understand how a company runs its business is known in the literature as a business model. According to [59], the business model is used for the analysis, evaluation, and comparison of results and for management, communication, and innovation. Moreover, the business model defines how the company defines its competitive strategy through the products and services offered on the market, how it benefits from it, how it generates costs, and how it differs from its competitors in terms of value proposition. At work ([60], p. 6), a sustainable business model is defined as a model that helps "describing, analyzing, managing, and communicating a company's sustainable value proposition". Moreover, the model explains how to create and deliver this value to the market and how to capture economic value for the company. As [60] emphasizes, all these processes take place while maintaining or regenerating natural, social and economic capital outside the company's borders. With increasing pressure on the circular economy (CE), business model innovation and making it sustainable has emerged as a key issue. Sustainable Business Models (SBMs) have become a tool for coordinating environmental, social, and business innovation. In this way, sustainable business models protect the environment while improving people's quality of life [1]. A key issue for sustainable business models is innovation and related technology [61]. Innovations for sustainable development are innovations that have a significant positive impact on the environment and society by changing the way organizations create and capture value. Innovations for sustainable development are also those that significantly reduce the negative impact on the environment and society when creating and capturing value [59]. Thus, innovations for sustainable development not only focus on economic profit, but also on social and environmental benefits. This means that they may not be profitable at the beginning but may become profitable in the future due to regulatory changes or social expectations. Based on sustainable innovations, business models known as sustainable are created. These are all business models based on closed-loop [62], natural capitalism [63], CSR [64] social enterprises [65], product service systems (PSS) [66], and blue economy [67].

The prototypes of sustainable business models have become the object of scientific inquiry and have adopted the name of sustainable business models archetypes. In this way, subsets of the set of sustainable business models were created. In the work [59], based on the analysis of literature and examples from practice, eight archetypes of sustainable business models were distinguished. They are presented in Table 2.

Table 2. Archetypes of SBM.

Grouping	Archetypes of SBM	Description
Technological (technology-oriented innovation)	Maximize material and energy efficacy	Do more with less resources, less waste, emissions, and pollution
	Create value from "waste"	Convert waste streams into useful and valuable input for other production
	Substitute with renewables and natural processes	Reduce your environmental impact by eliminating the "growth constraints" associated with non-renewable resources and current production systems
Social (society-oriented innovation)	Deliver functionality, rather than ownership	Provide services that meet the needs of users without the need for physical products
	Adopt a stewardship role	Actively work with all stakeholders to ensure their long-term health and well-being
	Encourage sufficiency	Provide solutions that actively seek to reduce consumption and production
Organizational (organization-oriented innovation)	Re-purpose the business for society/environment	Deliver social and environmental benefits instead of maximizing economic profit
	Develop scale-up solutions	Deliver sustainable solutions on a large scale to maximize social and environmental benefits

Source: Based on [59].

Maximize material and energy efficacy is an archetype that encompasses sustainable industrial development, i.e., maximizing material productivity, resource efficiency, and reducing waste. It is based on concepts such as lean, eco-efficiency, and cleaner production approaches. Improving resource efficiency and reducing waste and emissions is achieved by redesigning products and production processes [68,69]. The archetype aims to mitigate the environmental impact of industry by reducing energy and resource requirements. *Create value from "waste"* is an archetype that tries to identify and create a new value from what is currently perceived as waste. It aims to mitigate the environmental impact of industry by reducing resource demands, closing material loops, and using waste streams as input for other products and processes [70,71]. *Substitute with renewables and natural processes* is an archetype that draws inspiration from the processes taking place in nature and is based on the potential of renewable resources. This archetype reduces the environmental impact of industry by engaging renewable resources and natural processes to create more environmentally friendly industrial processes [72,73]. *Deliver functionality, rather than ownership* is an archetype that is based on product service systems (PSS) and servitization. As a result, companies are changing their business model from offering a manufactured product to offering a combination of a product and a service. In this way, the link between production and profit is broken. In addition, the efficiency of manufactured products is increased, as well as their durability and life. In this way, the demand for resources is reduced while at the same time using them more efficiently. However, the archetype requires a change in consumption patterns by reducing the need for consumers to have the product. It also requires changing production patterns by designing products that are more durable, upgradeable, and repairable. It also requires a link to waste innovation [74–76]. *Adopt a stewardship role* is an archetype that aims to maximize the positive impact of the company on the environment and society. It means improving the well-being of employees, developing communities by investing in their education and livelihoods, sustainable food crops and harvesting, protection of environmental resources and biodiversity [77]. *Encourage sufficiency* is an archetype that seeks to reduce consumption and change consumption patterns through the use of secondhand products (e.g., secondhand items and clothes) [78]. It enables goods to be delivered to low-income buyer markets. *Repurpose the business for society/environment* is an archetype based on social enterprises. The "hybrid business model" is a model in which two economic entities coexist. One acts as a for-profit company but uses some of the profit to finance the other non-profit entity. *Develop scale-up solutions* is an archetype that aims to disseminate sustainable business models. They can be based on franchising and licensing and are designed to allow for rapid duplication with local financing and local adaptation.

The work [59] made it possible to select subgroups of sustainable business models. This approach opens the possibility of performing interesting analyzes of emerging business models. However, the article [60] shows how quickly business models can evolve and adapt to changing realities. Thus, we can expect that the archetypes of sustainable business models will also evolve over time and most likely will be expanded by new subgroups. This was confirmed by the research described in [79], where 45 patterns to support sustainability-oriented business model innovation grouped in 11 groups were presented. In the context of the three pillars of sustainable development (ecological, social, and economic values), groups of these business models do not always implement all three of them. The taxonomy shows that two groups implement economic values (five—social values, two groups—ecological values) and only two groups implement values integrating all three pillars.

Although the archetypes of sustainable business models presented are criticized for insufficient representation of social issues, we decided to categorize sustainable business models based on this work. We realized that the projects covered by our analysis would be more technical than socially oriented. The archetypes of sustainable business models presented in the work [59] and the education of engineers in accordance with the Project-Based Learning concept inspired us to pose the following research questions:

Research question 4: What archetypes of sustainable business models can be classified as PBL innovations?
Research question 5: Which specialists initiate innovations related to particular archetypes of the sustainable business model?

3. Materials and Methods

3.1. Subject of the Research

One of the leading technical universities in Poland was selected for the study, in which, as part of the project "Silesian University of Technology as a Centre for Modern Education based on research and innovation" co-financed by the EU under the European Social Fund, interdisciplinary projects responding to the needs of Industry 4.0 are implemented on a large scale. The aforementioned projects were selected through a competition organized by the authors of the article. The projects were implemented based on the Project-Based Learning (PBL) teaching method. Project-based education is a learning model that includes learning methods focused on significant and challenging problems and engaging students in projecting, problem solving, decision making, and research activities [80,81]. This approach may be understood as didactic innovation integrating theory and practice by solving problems arising from professional life [82]. Recruitment in the competition for projects implemented in the form of PBL takes place in several stages [83]. The first was an electronic submission of the project. Based on the applications submitted, a catalog of proposed projects was prepared. This catalog was presented to students at all-university discussion panel devoted to PBL projects. The attendants were asked to prepare posters about their projects to attract students and encourage them to take part in a given project. The aim of the all-university discussion panel was to contact the main and auxiliary supervisors from different faculties with students from the whole university. Due to this action, project teams were created, and they detailed the project proposals and sent them for evaluation to the PBL competition. The project proposals consisted of six parts: (1) scientific goal of the project, (2) the importance of project results for the development of Industry 4.0, (3) research plan, (4) research methodology, (5) research effects, and (6) project budget. The received projects proposals are first divided into areas of knowledge and then sent for evaluation. Experts from various scientific disciplines were appointed to evaluate the competition applications. Each application was evaluated by two experts. The results of the competition were collected, analyzed, and approved by the Recruitment Committee, which included representatives of the project management team financed by the EU, representatives of the University's didactic and academic teachers, representatives of students, and the education expert. When the project was qualified for implementation, the project proposals became a form of business plan for the team, according to which the project ideas were implemented. In addition, the teams were required to detail the project proposals developed at the stage of recruitment and to prepare a detailed schedule, budget, or responsibility matrix.

3.2. Sample

The research included 49 projects conducted at the Silesian University of Technology. The projects were implemented in the years 2018/2019 and 2019/2020. Each project was implemented by a multidisciplinary project team consisting of 3 scientists, six students from various faculties, and experts from the business environment of the studied university. Thus, 146 scientists, 282 students from the Silesian University of Technology, and 126 experts from the university's business environment were involved in the projects. The structure of engaged scientists and students by faculty is presented in Table 3, while the structure of engaged experts by research area is presented in Table 4.

Table 3. Scientists and students from faculties involved in PBL.

Faculties	Number of Researchers	Number of Students
Faculty of Architecture	9	17
Faculty of Automatic Control, Electronics, and Computer Science	32	69
Faculty of Civil Engineering	18	34
Faculty of Chemistry	11	24
Faculty of Electrical Engineering	9	19
Faculty of Mining, Safety Engineering, and Industrial Automation	5	10
Faculty of Biomedical Engineering	8	16
Institute of Education and Communication Research	2	2
Faculty of Energy and Environmental Engineering	30	52
Faculty of Materials Engineering	3	6
Faculty of Mechanical Engineering	17	28
Faculty of Organization and Management	2	5
Total	146	282

Source: own study.

Table 4. Experts involved in PBL.

Research Area	Number of Experts
Automation and Robotics	36
Biomedical Engineering	23
Material Engineering	20
Construction	21
Environmental Engineering	26
Total	126

Source: own study.

3.3. Data Collection

The study covered 49 projects completed under Project-Based Learning in the analyzed period (2018–2020). First, access to written reports on the implementation of projects was obtained, which contained a description of the issues representing the research questions posed in the article, followed by a qualitative analysis of their content [84]. The data generated during the content analysis were collected and organized in an Excel spreadsheet, resulting in an organized data set with a clear structure increasing readability. Subsequently, the reporting records for each project were read to understand the issues discussed, and for the analyzed projects the general categories of sustainable business goals (SDGs) and business model archetypes (SBMs) were deductively determined. The framework presented in Tables 1 and 2 was used for this, giving our research a "general sense of reference". Then, in the next coding step, the justification for selecting SDGs (Table 5) and the justification for selecting SBM (Table 6) were inductively defined and matched to the existing concepts, allowing the emergence of new knowledge [85]. To that end, the extent to which these broad categories of SDG and SBM were represented in derived data from reports was first examined, and based on the relevant aspects that emerged from the data, these broad categories were inductively narrowed down to yield a larger set of lower-level categories that served as codes. Then, frequency analysis was used [86] to indicate the frequency of SDG and SBM codes. Subsequently, SDG and SBM codes were checked for consistency and compared to obtain reliability between the encoders [86], thus summarizing the encoding process.

Table 5. SDGs coding.

SDG	Coding: The Justification for Choosing a Sustainable Development Goal	Number of Repetitions
11—Sustainable Citiesand Communities	Creating an application enabling the strengthening of efforts to protect and safeguard the world's cultural and natural heritage	1
	Broadening knowledge on the use of waste in construction	3
	Broadening knowledge on the design of environmentally friendly buildings	1
	Developing technology related to transport	1
	Use of innovative LGS technology in construction	1
12—Responsible Consumption and Production	Broadening scientific knowledge in the field of improving materials of natural origin for use in construction	2
	Broadening knowledge on the impact of insecticides on the environment	1
	Broadening knowledge on the production of biodegradable materials and their application in environmental engineering	1
	Development of environmentally friendly materials	1
	Broadening knowledge in the use of technologies for obtaining metals from electronic waste	1
	Broadening knowledge on the use of sewage waste in construction	1
3—Good Health and Well-Being	Raising the technological level of equipment conducive to lowering premature mortality due to non-communicable diseases	6
	Increasing the technological level of equipment conducive to care of the elderly	3
	Broadening knowledge and developing a prototype of an implant supporting the fracture healing process	1
	Broadening knowledge and developing a simulation tool for the design of miniaturized diagnostic equipment	1

Table 5. *Cont.*

SDG	Coding: The Justification for Choosing a Sustainable Development Goal	Number of Repetitions
6—Clean Water and Sanitation	Broadening scientific knowledge in the field of water protection and wastewater treatment	2
	Broadening knowledge in the field of access to information on the quality of lakes	1
7—Affordable and Clean Energy	Broadening knowledge in the field of biogas production	1
	Broadening knowledge in the field of compressed air energy storage	1
9—Industry, Innovation, and Infrastructure	Raising knowledge and building prototypes in the field of unmanned traffic management systems (drones)	1
	Broadening knowledge and building prototypes using 3D printing for use in construction	1
	Increasing the quality of infrastructure, increasing the technological level of the industrial sector	1
	Broadening knowledge of the needs and expectations of employees related to the development of advanced information solutions	1
	Development of composite panels made in the technology of manual lamination and infusion in construction	1
	Improving knowledge and developing a system in the field of off-road vehicle behavior on the road	1
	Increasing knowledge and building prototypes in the field of diagnostic systems for buildings	2
	Broadening knowledge about equipment using haptic technology	1
	Construction of a test stand enabling the performance of tests of real structures in the non-linear stage of work	1
	Development of technology related to autonomous platforms (AGV vehicles)	3
	Broadening knowledge on the use of 3D printing in construction	1
	Broadening knowledge about the advantages and difficulties of implementing BIM in the design of building structures	2
	Broadening knowledge in the field of using technology simulation in plastics processing	1
	Broadening knowledge of the use of databases to analyze changes in the environment	1
	Broadening knowledge in the field of the possibility of using vacuum soldering	1

Source: own study.

The coding process was independently conducted by two researchers—the defined categories were verified for consistency and compared to obtain reliability between the coders [86]. During content analysis, the characteristics of the projects in terms of the SDGs assigned to them were also determined, the research area assigned to each project was identified, and the gender composition of the team was verified.

Table 6. SBM coding.

The SBM Archetype	Coding: Justification for Choosing the SBM Archetype	Number of Repetitions
Maximizing material and energy efficiency	Production optimization	3
	Eliminating time and energy waste through automation and robotization	10
	Creating environmentally friendly materials	1
	Reducing energy consumption of buildings	1
	Eliminating resource waste for subsequent additional treatment	1
	Increasing performance of the device	1
	More efficient building design	2
	Eliminating energy waste	1
	Eliminating material waste	1
Substitute with renewables and natural processes	Use of wood as a renewable material	1
	Replacing power sources with ecological ones	1
	Refinement of wood-based materials	1
Adopt a stewardship role	Protection of biodiversity and regeneration of environmental resources	1
	Caring for the needs of employees	1
	Improving the well-being of society	1
	Education and care for the health of society	8
Create value from "waste"	Use of waste for production	6
Not applicable	Not applicable	8

Source: own study.

3.4. Data Analysis

After the process of classifying the researched projects into categories, further analyses were performed. The data collected as a result of coding and classification were categorical, so the data analysis process was adapted to this type of data [87]. Therefore, the techniques of visualization were used, i.e., bar chart, stacked bar graph and table [88]. The bar chart visualizations made allowed for the data analysis in terms of the frequency of occurrence of a given category. On this basis, conclusions were drawn about the rankings of individual categories and the dominant value. These analyses allowed us to answer the first and fifth research questions. Stacked bar graph and table visualizations were typically performed to compile two categorical variables. This allowed for the analysis of the conditional distributions of these variables and to deduce the influence of one variable on the other. These analyses allowed us to answer the second, third, fourth, sixth, and seventh research questions.

4. Results

4.1. Analysis of Projects in Terms of SDGs

4.1.1. Goals Implemented in Projects

To answer the question of what goals of sustainable development are considered in PBL, the bar chart shown in Figure 1 was prepared. Its analysis shows that the most common goal of sustainable development is 9—Industry, Innovation, and Infrastructure. The second most popular is 3—Good Health and Well-Being. In turn, the least frequently pursued goal is 7—Affordable and Clean Energy.

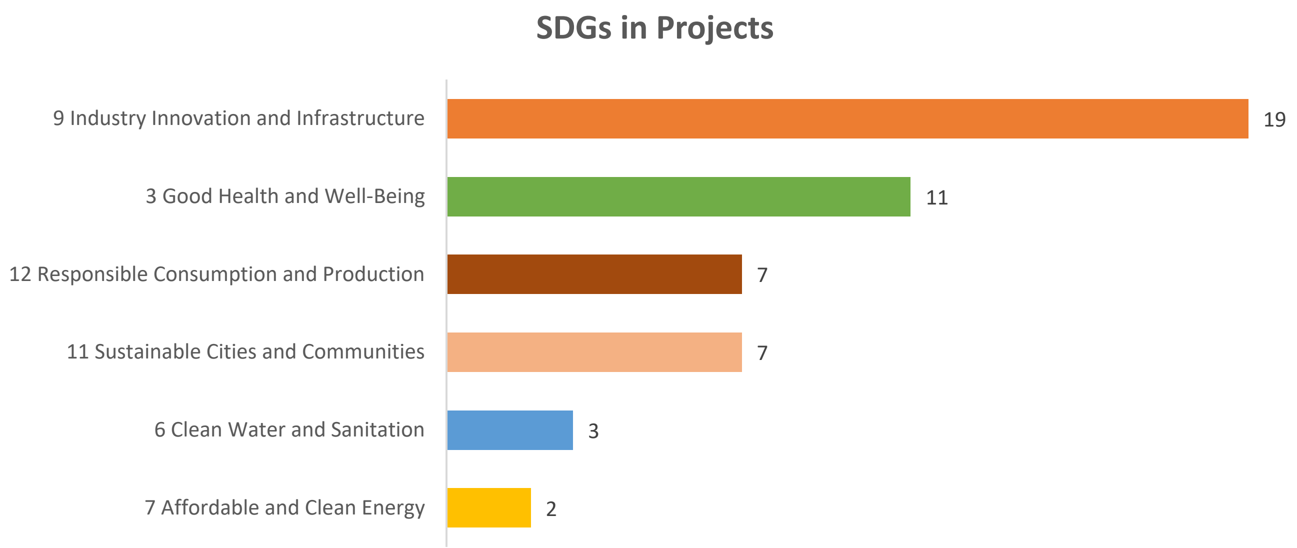

Figure 1. Sustainable Development Goals in projects. Source: own study.

4.1.2. Sustainable Development Goals and Research Areas

Figure 2 has been prepared to determine which specialists are interested in particular goals of sustainable development. It summarizes the SDGs tackled in the projects analyzed in the context of research areas. When developing this figure, we used the data contained in Table 5 which we additionally enriched with data on research areas. It allows to establish that the most popular research area is Automation and Robotics. Projects implemented in this area most often focus on goal 9—Industry, Innovation, and Infrastructure. The second most popular research area is Environmental Engineering. Specialists in this area focus on the goals: 11—Sustainable Cities and Communities, 12—Responsible Consumption and Production, 6—Clean Water and Sanitation, and 7—Affordable and Clean Energy. Specialists from the third most popular research area, i.e., Biomedical Engineering, focused on achieving goal 3—Good Health and Well-Being.

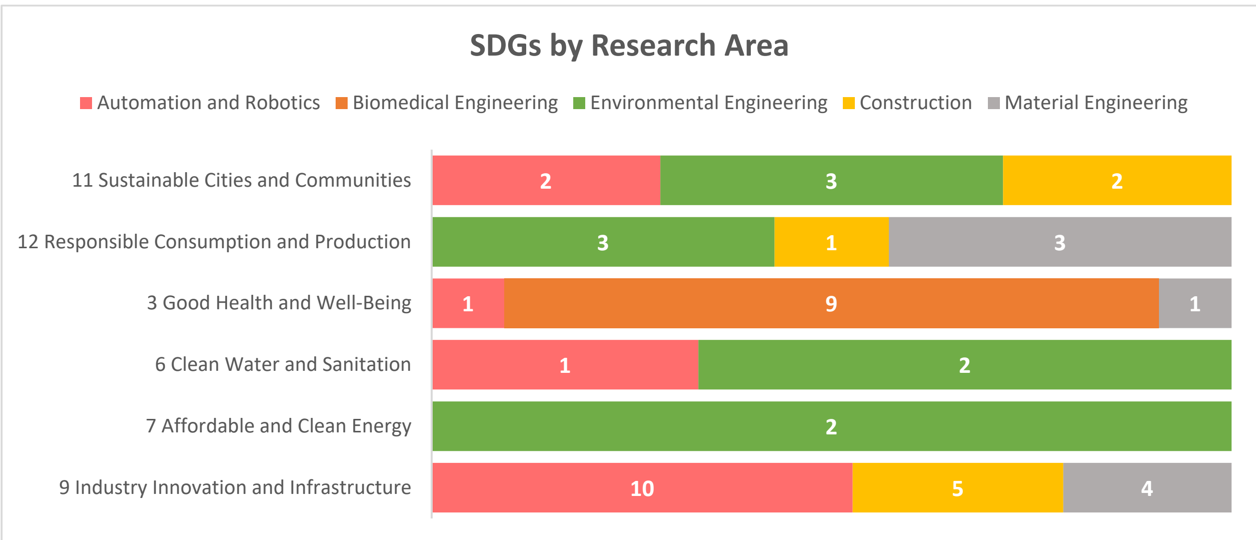

Figure 2. Sustainable Development Goals by research area. Source: own study.

4.1.3. Sustainable Development Goals and the Characteristic Technological Terms of Projects

To determine the characteristics of individual projects depending on the goal pursued, the following Tables 7–12 were prepared.

Table 7. Characteristic technological terms of projects for Industry, Innovation, and Infrastructure.

SDG	Research Area	Characteristic Technological Terms of Projects
9—Industry, Innovation, and Infrastructure	Automation and Robotics	Scene description algorithms around the AGV vehicle
		Unmanned aerial platform for building diagnostics
		Unmanned cargo aircraft (Cargo UAV), CFD simulations and analysis,
		A complete system that lets you obtain measurement data describing the behavior of the vehicle on the road, its surroundings and road conditions
		Development of a database enabling spatial analysis with the use of tools available from the QGIS program
		Development of vehicle models equipped with automation systems that enable the maintaining of a set speed to maintain a controlled distance between vehicles
		AGV vehicle, hydrogen cell-based power system,
		Prototype of the device control system with Haptic Feedback
		Industry 4.0, the quality of the work environment, the needs, and expectations of employees in technologically advanced enterprises, employee satisfaction
		An inspection and diagnostic robot to assess the condition of a building, diagnose building structures, improve on the safety of building structures
	Construction	3D printing from materials used in construction
		concept of a pump for feeding cement-based mixtures for 3D printing
		3D BIM model of the building
		Test stand for deformation control
		BIM implementation
	Material Engineering	3D printing with metal powders, SLM manufacturing technology
		Electroactive organic layers on inorganic surfaces, electropolymerization, electrochemical reduction of diazonium salts, use in optoelectronic devices
		Composite panel, fan cooling tower housing, structure optimization
		Simulation techniques applied in plastics processing

Source: own study.

Table 8. Characteristic technological terms of projects for Good Health and Well-Being.

SDG	Research Area	Characteristic Technological Terms of Projects
3—Good Health and Well-Being	Automation and Robotics	Automated design and virtual prototyping of new structures and microfluidic systems
	Biomedical Engineering	A prototype model of a new generation short-term metal implant with controlled stiffness; determining the conditions for the manufacture of the implant
		A virtual reality application to assist architectural design for the elderly
		An application supporting the elderly in coping with Alzheimer's
		Combining 3D imaging with CFD models for blood flow through the coronary arteries, validation of the CFD model, virtual platform for surgical procedures
		Microcircuit for human cell culture, synthetic and biological experiment
		Conceptual design of a robot in the form of a table containing such elements as: telephone, thermometer, blood pressure monitor, stethoscope, camera, motion meter
		Prototype of an autonomous platform built on omni-directional wheels, patient support
		A prototype of a toy using biofeedback for therapeutic purposes
		technologies supporting the functioning of an elderly person
	Material Engineering	Development of an effective method of applying photoactive organic coatings with antibacterial properties

Source: own study.

Table 9. Characteristic technological terms of projects for Responsible Consumption and Production.

SDG	Research Area	Characteristic Technological Terms of Projects
12—Responsible Consumption and Production	Construction	Improvement of wood properties: compressed wood with increased strength
	Environmental Engineering	Cellulose, usefulness of sewage sludge as an additive in the production of building materials
		Membrane production methods, sol-gel method, and wet phase inversion method; modern, ecological, and biodegradable material—hybrid membranes
		The use of plant protection products, the use of neonicotinoids in agriculture and their impact on the mass extinction of bees
	Material Engineering	Structural features of a biodegradable composite based on coniferous wood
		Optimizing the recovery of metals from electronic waste
		Polymer and halloysite nanostructured composite membranes

Source: own study.

Table 10. Characteristic technological terms of projects for Sustainable Cities and Communities.

SDG	Research Area	Characteristic Technological Terms of Projects
11—Sustainable Cities and Communities	Automation and Robotics	Automatic parking and vehicle recalling algorithms
		Mobile application using augmented reality (AR), methods of object detection and location, creation, and transformation of digital models
	Construction	CO_2 emissions for a residential building
		LGS technology, BIM tools, SMART systems, adjusting to people with disabilities, creating a catalog of typical footbridges in LGS technology for use in public spaces
	Environmental Engineering	Immobilization of municipal waste in cement mortars
		Checking the possibility of using aggregate with the addition of metallurgical waste, closed-loop management, improvement of the environment
		Management of municipal (hazardous) waste as a component of concrete mixtures

Source: own study.

Table 11. Characteristic technological terms of projects for Clean Water and Sanitation.

SDG	Research Area	Characteristic Technological Terms of Projects
6—Clean Water and Sanitation	Automation and Robotics	Analysis of algae blooms in water reservoirs, information about the condition of water on the Internet
	Environmental Engineering	Floating automated measurement system for environmental research, software for automatic measurement data analysis
		Biological reactor control and monitoring system, elimination of fats from wastewater through the biocenosis of microorganisms, FISH molecular technique

Source: own study.

Table 12. Characteristic technological terms of projects for Affordable and Clean Energy.

SDG	Research Area	Characteristic Technological Terms of Projects
7—Affordable and Clean Energy	Environmental Engineering	Energy storage in compressed air (the underground storage is a mining pit), the problem of energy surpluses in the periods of energy valleys in Silesia
		Production of energy from biogas, use of the obtained microbiological vaccine for the process of decomposition of cellulose, which is a substrate for biogas production

Source: own study.

Goal 9—Industry, Innovation, and Infrastructure was carried out in the area of Automation and Robotics, primarily in the field of algorithms, models and prototypes related to vehicles, including unmanned vehicles. In addition, research on the needs and expectations of employees in technologically advanced enterprises was carried out, and an inspection and diagnostic robot was built for use in construction. In the construction area, projects related to BIM modeling and implementation as well as 3D printing of materials used in construction were carried out. In the area of material engineering, projects related to 3D printing with metal powders, simulation techniques in plastics processing, electroactive organic layers, and optimization of the fan cooling housing structures were implemented. (Table 7).

Goal 3—Good Health and Well-Being was primarily carried out in the area of biomedical engineering. The projects implemented prototypes and applications focused on supporting the processes of medical diagnosis. Several projects focused on solving the problems of the elderly (Table 8).

Goal 12—Responsible Consumption and Production was carried out in the construction area in a project improving the properties of wood. Apart from this, it was carried out in the area of environmental engineering in a project using sewage sludge in building materials and in a biodegradable membrane fabrication project as well as in a project related to a plant and bee protection agent in agriculture. In the area of material engineering, the following projects were carried out: biodegradable wood-based composite, metal recovery from electronic waste, and nanostructured composite membranes (Table 9).

Goal 11—Sustainable Cities and Communities was carried out in the area of environmental engineering in innovation projects related to waste management. In the area of construction, the analyses of CO2 emissions of a residential building were carried out, as well as the project of using LGS technology, BIM tools, and SMART systems to solve the problems of people with disabilities. In the automation and robotics area, projects were carried out regarding parking and vehicle recalling algorithms as well as an application for object detection and location (Table 10).

Goal 6—Clean Water and Sanitation was carried out in projects automating measurements in the aquatic environment and in the design of the control and monitoring system of a biological reactor for research on the elimination of fats from wastewater (Table 11).

Goal 7—Affordable and Clean Energy was carried out in the area of Environmental Engineering. The projects concerned energy storage in a mining pit and obtaining renewable energy from biogas (Table 12).

4.2. Analysis of Projects in Terms of Archetypes of Sustainable Business Models

4.2.1. Archetypes of Sustainable Business Models in Researched Projects

To analyze archetypes of sustainable business models, innovations from PBL can be qualified, and Figure 3 was prepared. The innovations on which the projects were worked on were qualified for the SBM Archetype called "maximize material and energy efficacy". The archetype of "adopt a stewardship role" was in second place. The least numerous archetypes were "create value from "waste"" and "substitute with renewables and natural processes". Eight innovations were not classified under any of the considered archetypes.

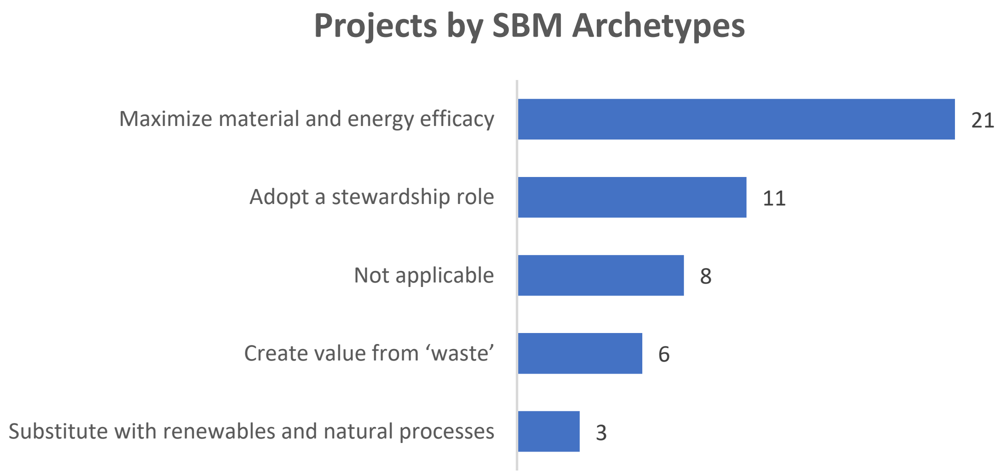

Figure 3. Projects by SBM archetypes. Source: own study.

4.2.2. SBM Archetypes and Research Areas

To diagnose which specialists initiate innovations related to particular archetypes of the business model, Figure 4 was prepared. It summarizes the SBM archetypes related to the projects analyzed in the context of research areas. When developing this figure, we used the data contained in Table 6, which we additionally enriched with data on research areas. The "maximize material and energy efficacy" archetype aroused the interest of specialists from all the research areas under consideration. The archetype of "adopt a stewardship role" included innovations in the field of automation and robotics, biomedical engineering, and environmental engineering. However, most projects were carried out by specialists in the field of environmental engineering. The archetype of "create value from "waste"" included specialists in the areas of environmental engineering and material engineering. The archetype "substitute with renewables and natural processes" included innovations in the field of automation and robotics, construction, and material engineering.

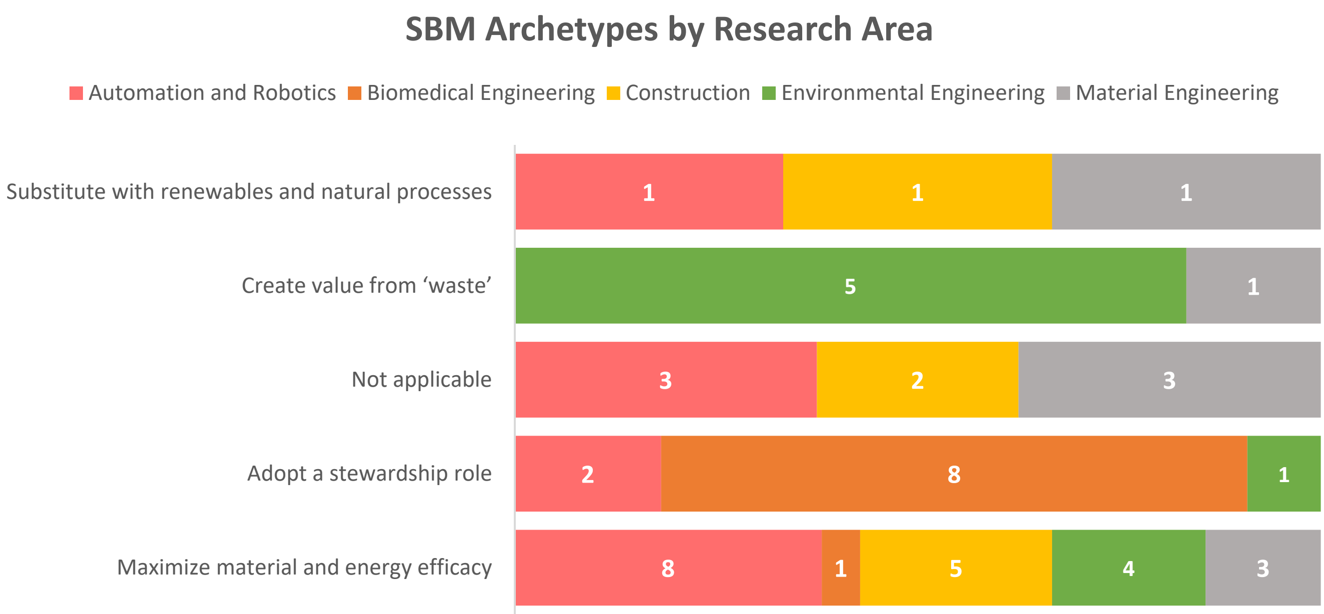

Figure 4. SBM archetypes by research area. Source: own study.

5. Discussion

The article poses five research questions. Three of them concerned innovations implementing SDGs, and two more related to innovations related to SBM archetypes.

Answering the questions related to the innovations implementing SDGs, it was found that in the studied university the didactic projects carried out using the PBL method most often referred to the two goals of sustainable development, i.e., 9—Industry, Innovation, and Infrastructure and 3—Good Health and Well-Being. Moreover, it was found that specialists in the research areas defined as (1) automation and robotics and (2) environmental engineering were most often involved in innovations related to SDGs.

Answering the research questions related to SBM archetypes, it was found that the innovations of the researched projects could most often be classified into two SBM archetypes, i.e., (1) maximize material and energy efficacy and (2) adopt a stewardship role. The first of these archetypes enjoyed the involvement of specialists from all the research areas under consideration. The second one was dominated by specialists in the field of biomedical engineering. However, not all of the proposed innovations could be classified as SBM archetypes (8 were not qualified). Specialists whose innovations could qualify for SBM are mainly specialists in the areas of automation and robotics, environmental engineering, and biomedical engineering.

Analyzing the contribution of universities to the achievement of goals related to the achievement of SD, emphasized in the literature, it can be concluded that the curricula implemented by universities should enable students to develop their competences in this field. This is shown in various studies (e.g., [57,58]) which emphasize that the inclusion of SDGs in education requires the implementation of innovative pedagogical methods to acquire these competences. Our research shows that Project-Based Learning and the interdisciplinary approach can be these innovative methods because they enable real and empirical learning about SDGs as well as a comprehensive view of the analyzed problem, and as researchers emphasize (e.g., [56]), these are the conditions necessary for the successful implementation of SD in education.

The results of our research confirm that technology is the key to more sustainable production. This confirms the conclusions also included in the work [61]. The results of our research show the domination of such a research area as automation and robotics. Therefore, we confirm the conclusions drawn by researchers in their work [1] regarding the enormous importance and contribution of this technological area to sustainable development. Moreover, the next two most popular areas were environmental engineering, focused on environmental amenities, and biomedical engineering focused on the needs of society, which indicates the importance of all 3 pillars in achieving SDGs and is in line with the need to implement innovations based on all three pillars of SD [4] that is emphasized by researchers. The classification of innovations performed by us (developed as part of the researched projects) in relation to the archetypes of sustainable business models confirms the conclusions [1] about the key impact of technology on the economic and environmental dimension of sustainable development. Moreover, in the ranking of the most popular business models we diagnosed, the model called "adopt a stewardship role" also allowed us to confirm the impact of technology on the social dimension. While Bocken [59] presents eight archetypes of sustainable business models, we only identified four of them. On the one hand, the reason for this is the inductive approach to analysis, and on the other hand, the engineering approach to the implementation of the researched projects. In this way, most of the projects were oriented towards technological innovations, and only some of them were steered towards social innovations. It can be assumed that the implementation of these projects with greater research participation in the field of social sciences could increase the number of archetypes from the social and organizational group. In the context of the taxonomy of sustainable business models proposed in [79], it can be said that, most likely, using this classification would allow us to classify the design innovations studied by us into groups creating mainly ecological values. This is because most of the project innovations we studied were related to the circular economy, e.g., eco-design and closing the loop.

5.1. Implication for Research and Practice

This article contributes to the literature on sustainable technologies and from the perspective of universities educating engineers with the use of Project-Based Learning, thus extending the concepts of the project approach in education to the issues of sustainable development and elaborating an argument for a greater emphasis on educating engineers through Project-Based Learning.

In practice, the article responds to the needs of all entities involved in activities for sustainable development (e.g., companies, educational institutions, government organizations) by pointing to those technological areas that contribute to the implementation of the SDGs to the highest extent. Our research also shows the relationship between the subject matter of undertakings (projects) and the possibilities of creating sustainable business models. Finally, our research shows other universities how to approach engineering education so that their undertakings can implement SDGs. The obtained results are therefore the basis for identifying the following recommendations for other universities wishing to implement a project approach in the education of engineers in the future: (1) It is necessary to give the appropriate importance to the implemented projects and link their topics with the problems reported by the socio-economic environment of the university, because only this can ensure that the implemented projects will respond to the real problems of enterprises and other organizations in their environment; (2) the use of an innovative pedagogical approach (in this case, a project approach and interdisciplinary teaching) to enable students to obtain practical knowledge in the field of SD requires that universities provide appropriate organizational conditions for the implementation of such pedagogical innovation, including, in particular, a properly planned recruitment process and promotion of this form of education among academic teachers and students, but also among organizations from the university's environment; (3) educating students through projects focused on the implementation of SDGs enables students to gain practical knowledge in this area and gives them greater opportunities on the labor market, where there is an increase in interest on the part of SD enterprises and the inclusion of SD in their business plans. It also allows graduates to set up their own startups focused on implementing SDGs. Hence, such innovative forms of education as a project approach or interdisciplinary education should be part of the core curriculum in each field of study. This, however, requires commitment on the part of the university authorities, appropriate funding, as well as adequate motivation for academic teachers.

Furthermore, the concept of engineers' education presented in this article can be extrapolated to other universities. Our university meets with the interest of other universities in this form of education. For example, as part of the summer school, we conducted lectures for a Chinese university, during which we presented the most important issues of such education. In addition, our university, as a member of the Eureca-pro consortium, which includes seven universities forming the nucleus of the future European University which focuses on broadly understood issues related to the SDGs, we promote our project and the results obtained within it, as well as we share experiences from its implementation. Our project can be compared to other projects carried out at foreign universities, from which we drew inspiration, for example, Stanford University, but also to previous projects carried out at our university. It should be noted, however, that the earlier projects carried out at our university had a smaller scope and complexity, because they were implemented at specific faculties, and not within the entire university.

5.2. Limitation

Our research has two main limitations. The first is bias by virtue of our direct role in managing the PBL competition and our involvement in the research and data analysis. It should be noted, however, that in order to mitigate the bias in this study, authors identified projects only by their title, without using information about the composition of researchers, students, and experts. In this way, the documentation of the projects was anonymized. Moreover, one of the authors conducting the coding and analysis process acts as a monitoring specialist in the analyzed project and does not directly organize the competition, but indirectly supports it by developing statistics and monitoring indicators. The second one is the population size of the studied projects. With 49 projects, we could not afford to use statistical tests, such as the chi-square test of independence, or more advanced analytical methods, such as correspondence analysis. Therefore, we treat this research as preliminary exploratory research. We plan to continue it, as the Project-Based Learning teaching method is being continued at our university. Therefore, in future research we will be able to increase the size of the study population and perform the aforementioned statistical analyses and even time dependency analyses.

5.3. Information about Ethics

This research followed the ethics regulations in place at the Silesian University of Technology.

Author Contributions: Conceptualization, M.P. and I.Z.; methodology, M.P. and I.Z.; formal analysis, M.P. and I.Z.; investigation, M.P. and I.Z.; writing—original draft preparation, M.P. and I.Z.; writing—review and editing, M.P. and I.Z.; visualization, I.Z.; funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Silesian University of Technology, grant number 13/040/BKM_21/0102 and 13/010/BK_22/0065.

Institutional Review Board Statement: The study was conducted in accordance with the ethics regulations of the Silesian University of Technology.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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