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Efficacy of Project Based Learning Approach in Upskilling Manufacturing Professionals in Industry 4.0 Technologies

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Abstract

This paper explores the transformative application of project-based learning (PjBL) within the framework of Industry 4.0 to address digital transformation challenges in manufacturing. Recognising that digital transformation is best taught through real-world implementation, we designed a specialised program directly engaging with the industry to identify and tackle critical operational issues. The curriculum was strategically upgraded to align with cutting-edge advancements in Smart Manufacturing, ensuring relevance and effectiveness. This paper presents the curriculum design approach and evaluates the program's success through detailed completed project case studies. While PjBL is increasingly acknowledged in academia for its ability to foster active, experiential learning, its application in higher education, particularly in the manufacturing sector, remains underexplored. The 6-month certification program, delivered by one of the leading universities to one of the world's largest steel manufacturers, not only bridged a significant skills gap in modern manufacturing but also delivered tangible organizational benefits, including a remarkable USD 8.5 million in cost savings annually.

1. Introduction

The rapid development of Industry 4.0 technologies, including the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and machine learning (ML), has radically reshaped the global manufacturing sector. These developments require a skilled workforce to apply and utilize digital tools to meet sophisticated operational challenges [1,2]. Nonetheless, conventional teaching methods do not equip professionals with the capability to meet these challenges, focusing on theoretical knowledge with inadequate practical implementations [3,4]. This skill mismatch is especially noticeable in the manufacturing industry, where embedding smart technology is essential for ensuring competitiveness and achieving the desired operational efficiency [2].

Manufacturing organizations increasingly use digital technologies to enhance product quality, track and minimize energy consumption to achieve sustainability objectives, carry out predictive maintenance practices, and use industrial robots in dangerous applications to maintain worker safety [3]. Despite these advances, numerous applications demand specialized skills, typically only at the time of initial implementation. Therefore, organizations are highly dependent on external vendors to deploy digitalisation solutions, which results in high vendor dependence and possible data privacy issues. This reliance typically leaves subject matter experts (SMEs) within the company powerless, since they do not possess the competency to apply, manage, or change these solutions on their own [5]. This encouraged us to create an academic curriculum integrating Project-based learning (PjBL) to upgrade manufacturing professionals.

PjBL, investigated globally since the 80s [6], is a method of teaching that has participants discover real-world problems and practical problems, and resolves them through practical projects. This technique, in addition to an increased understanding of theoretical concepts, also develops necessary skills like critical thinking, problem-solving, teamwork, and flexibility [3] [10]. PjBL enhances project management expertise, nurtures critical thinking, and collaboration skills, which are required of engineering professionals as highlighted by De Los Ríos et al. [11]. Integration of CAD/CAE tools within PjBL environments effectively helped improve design and analytical competency of the students, making them employment ready, as demonstrated by Berselli et al. [12]. Martinez et al. [14] explored the viability of PjBL in creating cooperation among heterogenous teams to solve industrial problems. Frank et al. [15] and Savage et al. [16] stressed the importance of integrating computer tools and simulation into

PjBL systems for learners to better handle the challenges of smart manufacturing. Joyce et al. [13] further explored the possibilities of PjBL by incorporating modules based on sustainability that promote ethical responsibility in addition to technical skill. Palmer and Hall [17] also observed the need for formalized feedback and responsive teaching techniques to meet problems such as differentiated learning styles and participation levels in PjBL settings. Hsieh and Knight [18] and Chidthachack et al. [19] pointed out checkpoints and monitoring progress in sustaining learners' motivation and making measurable achievements. Hernández-de-Menéndez et al. [20] and Zhang et al. [21] supported PjBL's application in the creation of critical thinking and technical competence, especially in energy optimisation and defect detection contexts. Zhang et al. [22] investigated experiential learning in hybrid laboratory courses, confirming the efficacy of experiential methods in developing problem-solving abilities.

Integrating PjBL into curricula that aim to develop students' skills in the field of Industry 4.0 has been researched as well. Hernández-de-Menéndez et al. [20] and Savage et al. [16] outlined the way PjBL allows students to learn and embrace digital technologies competently, to match industry expectations. Savage et al. [16] and Zhang et al. [22] highlighted how sustainability-focused PjBL enhances material and energy efficiency in engineering education. Ling Li, in her article on "Reskilling and Upskilling," states that in addition to technical skills, efforts must be towards imparting critical skills such as analytical thinking, creativity, and flexibility and calls attention to the lack of effectiveness of conventional schooling models, promoting experiential learning and life-long learning skills as strategic necessities for organisations. This view highlights the need for pioneering learning methods in fulfilling the changing demands of Industry 4.0 [5].

While existing research emphasises the effectiveness of PjBL in stimulating individual learning improvement, there exists a significant vacuum of its being implemented in the professional upskilling programmes addressed to organisational contexts [4] [3]. Such research is exclusively dedicated to undergraduates, bypassing the complexities inherent in switching industries for professionals in Industry 4.0 environments. Beyond this, even less evidence speaks to the demonstrable organisational return on using PjBL in terms of cost savings, reduction in downtimes, or enhancing efficiency levels [5] [7].

This work is aimed at empowering manufacturing professionals by developing an effective curriculum incorporating project-based learning (PjBL). Appropriate project selection is key to PjBL success. The project must be in line with the learners' skill levels, professional functions, and organisational requirements and offer chances to use sophisticated digital tools and methodologies covered in the curriculum [5] [8-7]. Additionally, it enables students to contribute to their organisation's digital transformation agenda, leading to a sense of ownership and engagement. [4] Kim et al. (2023) outlined an IoT implementation course at the graduate level that was developed in close collaboration with local industries and was able to bridge theoretical education with practical application [5]. These collaborations enhance personal skills and organisational pain areas, showcasing the potential for greater use of PjBL in professional environments [3].

In this paper, we discuss the outcomes of a six-month certification program in Smart Manufacturing, leveraging a PjBL approach developed by a leading university for employees of one of the world's largest steel manufacturers. It provides an in-depth examination of the processes involved in project selection, curriculum design and delivery, and project mentoring. Furthermore, this work highlights the tangible and intangible benefits gained by the organisation through the successful implementation of projects executed during the program.

2. Program Overview

2.1 Program Curriculum Development

The efficacy of PjBL depends mainly on the selection of projects and how they overlap with the course content. A well-chosen project bridges the gap between theoretical knowledge and practical application, ensuring that participants gain a deeper understanding of the concepts and their relevance in real-world scenarios [23]. In this study, the 6-month certification program was collaboratively developed by a leading university and industry experts to address specific pain points in the manufacturing processes of one of the world's largest steel producers. The curriculum was meticulously crafted based on insights gained from on-site visits to manufacturing plants by the academic team, where existing challenges were identified in consultation with the process owners and integrated into the learning modules. Figure 1 illustrates the key focus areas derived from 33 projects identified within the manufacturing plants to address these challenges. The program also prioritised identifying projects with low budgets but high returns on investment (ROI) to ensure seamless implementation and high employee and employer satisfaction with the program.

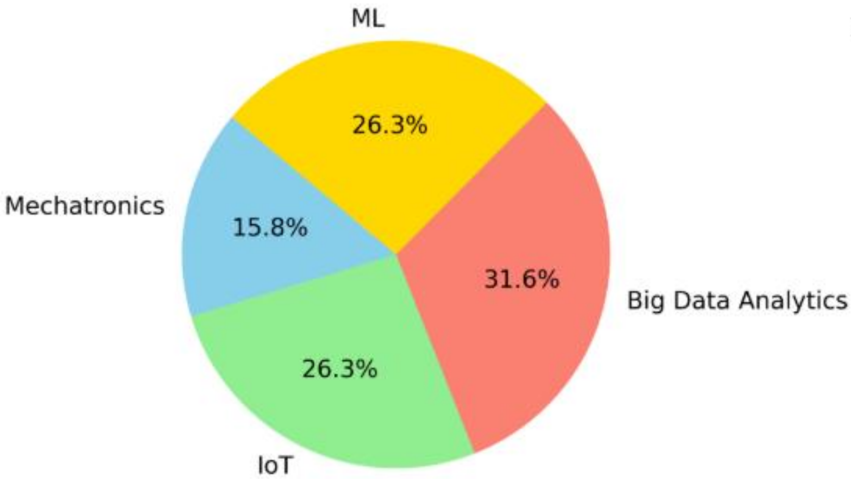

Figure 1: Key focus areas based on identified projects

2.2 Admission Criteria

Any undergraduate engineering degree in any of the disciplines is a mandatory requirement for this program. From over 200 applicants, 36 students were selected after going through a competitive and rigorous aptitude test. A mandatory requirement of at least three years of professional experience in the manufacturing sector was established to ensure participants fully understood manufacturing processes and industry operations and the confidence required to execute complex projects. The work experience distribution is shown in Figure 2.

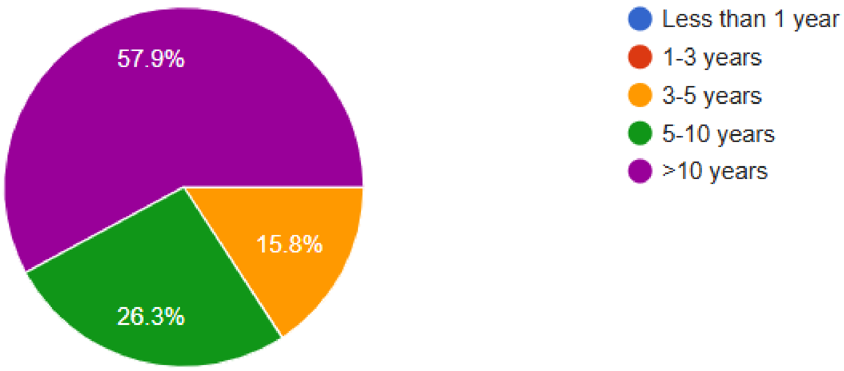

Figure 2: Student work experience in the manufacturing industry

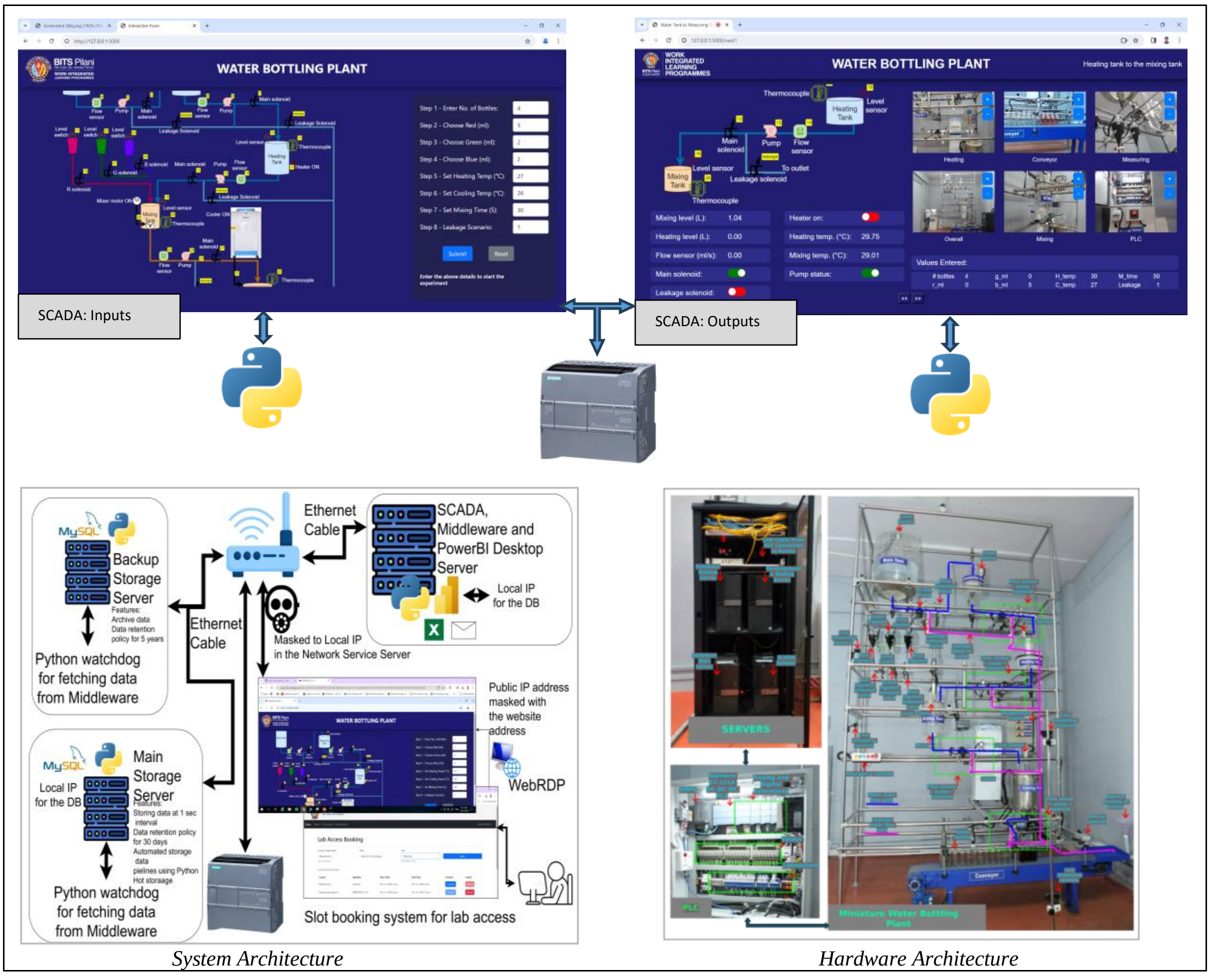

Figure 3: Remote lab for self-paced learning

2.3 Program Structure

Phase 1: Foundational Knowledge

At the beginning of this program, access was given to our in-house production-scale innovative water bottling plant (Figure 3) and online platforms with several self-paced modules (Figure 4). The self-paced study modules included 3-5 minute video lessons on numerous topics, followed by a randomly generated multiple-choice quiz comprising about 10 questions chosen at random from more than 50 questions stored in a question pool. When the participant scored below 95% marks, the participant was directed to basic concepts relating to the topic first before being redirected to the video lesson, and a second attempt at the quiz. The second try offered a different group of questions, and participants had to score at least 95% to advance to the next video.

For the hands-on, participants were given remote access to the water bottling facility, where they worked through four unique troubleshooting scenarios crafted to mimic actual industrial issues. Participants accessed leakages and system inefficiencies through dashboard analysis, data analytics, and computation. If they did not troubleshoot correctly, they were asked to go through a similar example emphasizing the basics of solving the type of problem before being sent to another troubleshooting situation that challenged the same knowledge. This repeated process strengthened industrial troubleshooting skills, allowing participants to interpret system data, recognize patterns, and use analytical reasoning to identify anomalies.

Apart from this, the program consisted of nine contact sessions focused on supervised, hands-on labs for the first three months. These labs were carefully designed to cover different aspects of Industry 4.0 to enable participants to apply the knowledge they gained in their project implementations. These labs were designed after the projects were selected to ensure that the different skills required in project implementation were covered. For example, in Mechatronics, hands-on lab focusing on adding a few different sensors required to build a digital twin was covered. This included how to modify the PLC ladder logic and this was taught using the Siemens TIA portal to modify the ladder logic virtually and test it. This activity taught them the methodology and provided the confidence to add new sensors to their actual process line. In Machine Learning (ML) hands-on activity, the schema of the data was obtained from their plant and populated with fake data to demonstrate how ML can be a powerful tool in process optimization. Similarly, for every course we designed relevant lab activities that they could directly apply at their workplace.

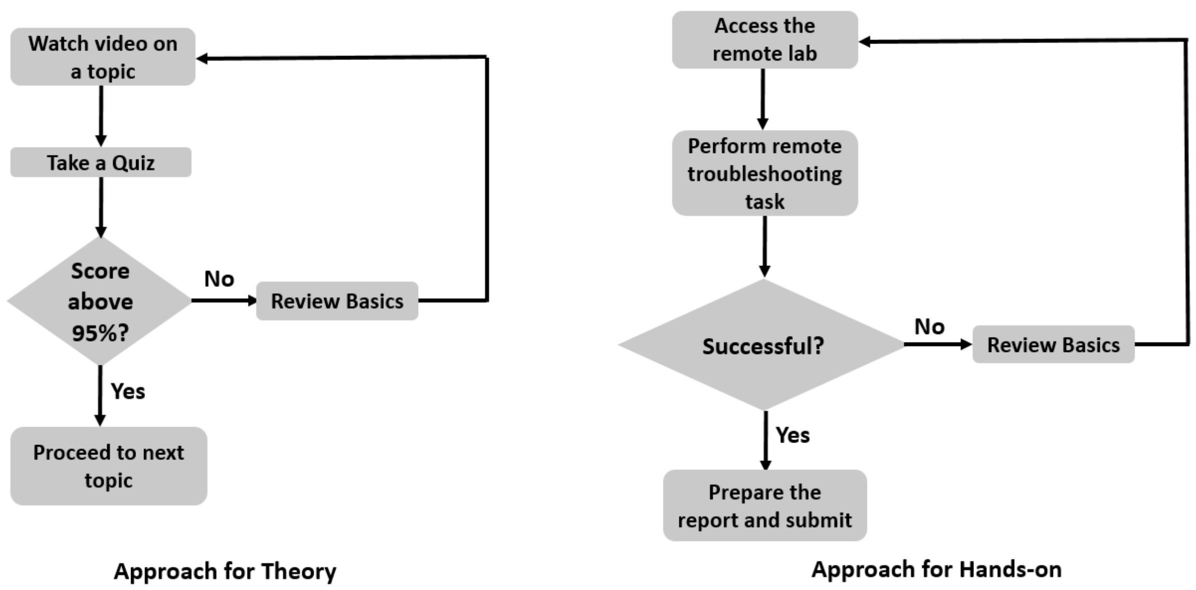

Figure 4: Self-paced learning approach

Phase 2: Real-Time Project Implementation

Industry-driven projects addressing real-time problems were part of the program's second phase. The total number of students enrolled in the program was 36, grouped into 9. Out of the 33 identified projects, nine were selected. Participants underwent training designed for each project to fulfil the requirements and apply theoretical knowledge to real, practical problems. On-site support was received from the faculty members, with visits to all the different locations of the project, which were undertaken nationwide. These on-site support visits helped ensure that the teams involved implemented the projects without any complications and within their respective timelines set for implementation, hence successful.

3. Results and Discussion

3.1 Results

The program's effectiveness was measured based on two criteria: the technical quality of the solutions developed and their impact on organisational performance. Some of the key outcomes included:

- **Reduced Machine Downtime:** Predictive maintenance solutions considerably reduced machine downtime.
- **Cost Savings:** The projects realized a total savings of $8.5 million yearly.
- **Improved Skill Acquisition:** The participants have enhanced problem-solving, critical thinking, and teamwork skills

Detailed overview about the individual projects and their outcomes are shared in Table 1.

Table 1. Projects and outcomes

#	Objective	Solution	Results
1	Automate defect detection in steel production to reduce rejection rates and waste.	Developed a real-time defect detection system integrated into the production line using image processing and deep learning.	**Annual savings of $442800** 92% reduction in rejection rate, improved production efficiency, and decreased material waste.
2	Optimise carbon measurement and reduce arc-to-tap times in steelmaking.	Introduced predictive analytics and optimised carbon measurement integrated with Level 2 systems.	**Annual savings of $3.66 million** Increased production throughput and reduced operational costs.
3	Automate inspection of grate bars in pellet cars to enhance efficiency.	Developed an automated image processing system with industrial sensors and cameras for real-time defect detection.	**Annual savings of $494400** Enhanced defect detection accuracy, improved operational efficiency, and extended equipment lifespan.
4	Monitor and optimise energy consumption in the steel plant.	Implemented a centralised real-time energy monitoring and analytics system with predictive maintenance alerts.	**Annual savings of $83244** Cost savings, improved energy efficiency, and support for sustainability goals.
5	Predict mechanical properties of steel to reduce reliance on tensile testing.	Developed machine learning models (Random Forest and XGBoost) for real-time property predictions.	**Annual savings of $195,600** by reducing testing dependency, improved quality control, and reduced processing delays.
6	Enable predictive maintenance for descaler motors in hot strip mills.	Integrated real-time monitoring with advanced hardware and human-machine interfaces (HMI).	**Annual savings of $134,400** through prevention of pump failures and reduced unplanned downtime.

7	Enhance security and reduce vendor dependency in predictive maintenance systems.	Transitioned predictive systems from vendor-managed cloud to on-premise solutions with SCADA integration.	**Annual savings of $23328** Reduced cybersecurity risks, improved reliability, and achieved operational independence with cost savings.
8	Reduce breakdowns in electrical control rooms through proactive temperature management.	Implemented IoT-enabled temperature sensors integrated with real-time alerts and monitoring.	**Annual savings of $15,600** Increased MTBF and reduced breakdown frequency with enhanced response times.
9	Automate ferroalloy addition in steelmaking for cost efficiency.	Developed a Python-based optimisation model with real-time inventory updates and predictive alloy addition.	Annual savings of $**3470675** Streamlined operations and ensured consistent steel quality.

3.2 Discussion of Results

The commonalities of the nine case studies presented in the paper highlight the transformative impact of the project-based learning (PjBL) approach, particularly in addressing the digital transformation challenges in manufacturing through hands-on, real-world problem-solving. Key impactful aspects include:

- Skill Development and Knowledge Application: The PjBL approach allowed participants to develop and apply critical digital skills such as data analysis, process optimisation, and machine learning. These skills were instrumental in creating innovative solutions and allowed participants to bridge their knowledge gap in digital technologies.
- Real-Time Problem Solving: Each case study tackled real, pressing operational issues in steel manufacturing. This hands-on approach ensured that participants could apply digital technologies, such as mechatronics, IoT, machine learning, and image processing, to solve practical problems effectively. For example, implementing predictive maintenance systems and energy optimisation models directly addressed inefficiencies in plant operations.
- Cross-Disciplinary Integration: The projects integrated multiple Industry 4.0 technologies (e.g., IoT, machine learning, and computer vision) and showed how these can be applied in diverse manufacturing contexts, from defect detection and energy optimisation to predictive maintenance and material property prediction.
- Quantifiable Results: Every case study provided measurable outcomes that proved the success of the PjBL approach. These included significant cost savings (e.g., $3.5 million in annual savings through predictive maintenance), efficiency improvements (e.g., 92% reduction in defect rejection rates), and enhanced operational metrics (e.g., reduced downtime, energy optimisation, and increased throughput).
- Sustainability and Operational Efficiency: Some projects focused on improving sustainability and operational efficiency, demonstrating the value of integrating digital technologies for long-term financial and environmental benefits. This was evident in projects related to energy monitoring and the reduction of material waste through optimised steelmaking processes.
- Scalability and Flexibility: Many solutions, such as the Ferro Alloy Optimization Model, were designed to be scalable and adaptable to future needs, underscoring the

long-term benefits of the PjBL approach in preparing professionals for ongoing digital transformations.

3.3 Student Feedback

Additionally, feedback was sought to understand how effectively the program content was designed to ensure successful project implementation. We also sought input to know how this project-based learning would enhance their performance, and in both cases, the results were satisfactory, as per the below Figures 5 and 6. These results underscore the potential of PjBL to address digital transformation challenges effectively while fostering meaningful skill development.

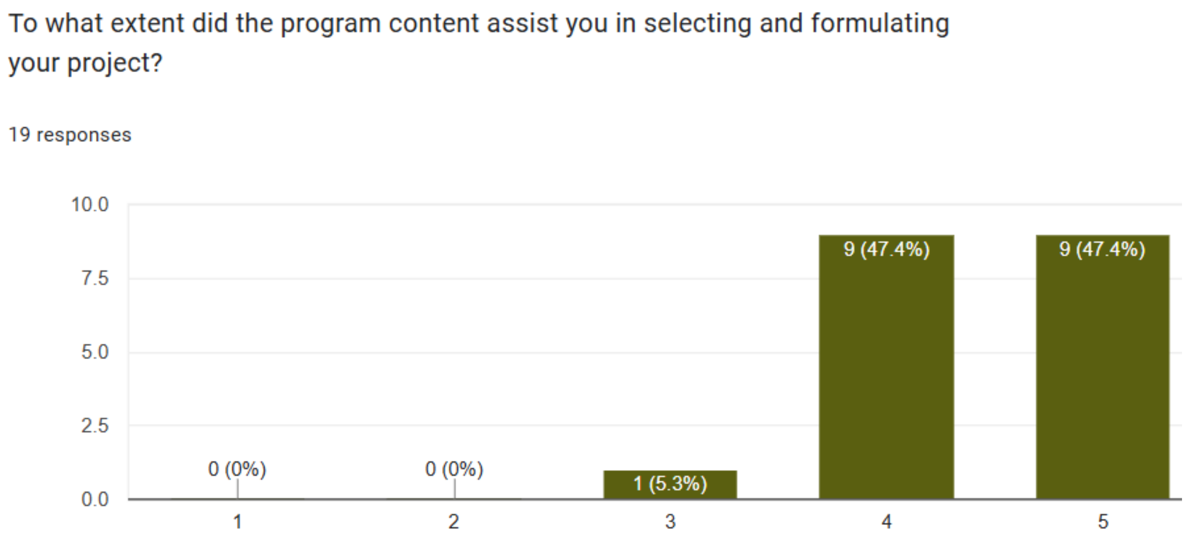

Figure 5: Student feedback on the content's relevance to the projects

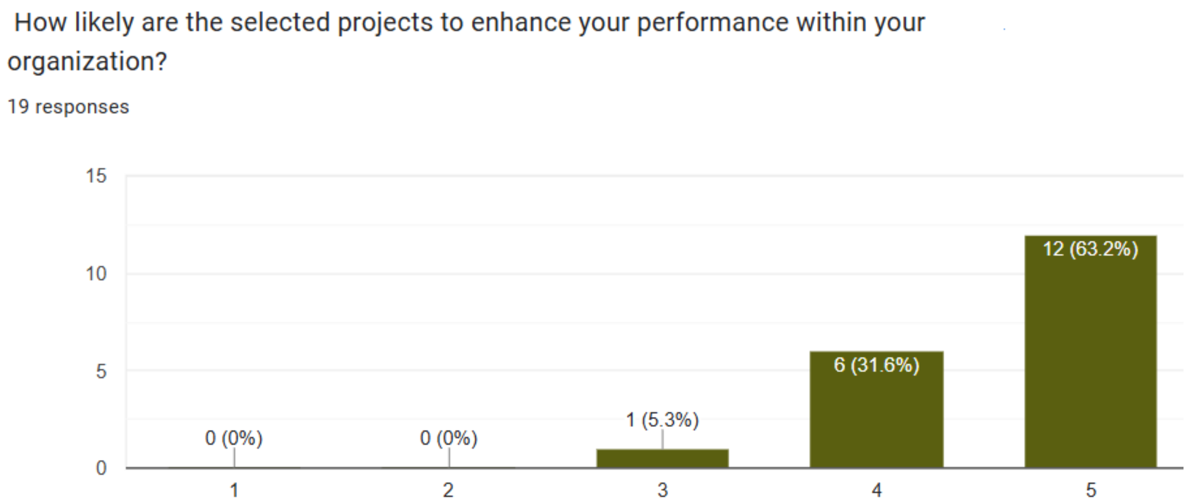

Figure 6: Student feedback on the project's relevance to their growth in the organisation

4. Conclusion

This paper provides compelling evidence for the efficacy of PjBL in developing Industry 4.0 competencies among manufacturing professionals. The 6-month certification program demonstrated that hands-on, problem-based learning could effectively overcome the challenges faced by professionals without prior digital experience. The PjBL approach proved highly impactful in developing Industry 4.0 competencies among manufacturing professionals, with clear, measurable improvements in skills development and organisational performance. The hands-on, industry-driven nature of the program ensured that the learning outcomes were directly aligned with the sector's needs, creating a strong foundation for future workforce transformation in manufacturing. The findings offer valuable insights for academic and industrial stakeholders seeking to enhance workforce skills in digital transformation technologies.

5. Future Work

Based on the success of this program, a second cohort with double the size of the pilot group has been released, and another batch of students from the same organisation is now on an expanded project-based learning program in Smart Manufacturing. One of the essential takeaways from this initiative is the dual learning process for both the students and the faculty. Faculty members also undergo considerable development through this approach, keeping educators and learners highly engaged. We recognise the importance of faculty upskilling and are actively working on enhancing faculty training as a critical component of such programs. We also develop advanced experiential learning content by combining extended reality technologies and creating more interactive, self-paced learning modules. These are intended to be memorable and impactful learning experiences. Moreover, we curate case studies from our program experiences to enrich Industry 4.0 courses, ensuring they remain relevant and deeply connected to real-world applications.

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