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PLM Education: The State of the Art and Future Trends

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Abstract: *New industrial initiatives and innovations are being brought forward at an increasingly rapid rate, radically transforming job profiles and imposing the need for new paradigms in engineering education. Over the last few decades, PLM has evolved into the key business paradigm for supporting companies' efforts to achieve long-term sustainable competitiveness by balancing innovation and efficiency growth on the one hand and cost optimization on the other. New labor market demands, shaped by rapid PLM evolution, require a shift in current engineering education to adapt to new realities and better prepare engineers for future challenges. This paper aims to provide a comprehensive review of the state of the art in PLM education, highlight issues facing PLM education, and discuss possible future trends and developments. The paper aims to increase awareness of the importance of PLM education development and encourage active debate about potential actions as responses to current issues.*

Keywords: *PLM concept, PLM education, engineering education*

1. INTRODUCTION

Over the last two decades, deep technological changes have occurred, influencing businesses and increasing the risk of changes in the labor market, necessitating a thorough discussion of what engineering education should be like in the future.

Analyses and forecasting of future work activity mainly point to the impact of digitization, new industrial initiatives, and technology-based business paradigms. Actually, current students should be prepared for professions that are still in their infancy. This implies that as new challenges arise in a changing environment, the demand for new skills and qualifications will increase. In order to meet modern industry qualifications and skills, education systems must evolve, adapt to new realities, and better prepare engineers for the future.

Passow [1] provided a list of engineering competencies required of for modern industry, which includes the ability to apply knowledge from mathematics, science, and engineering, design and perform experiments, analyze and interpret data, identify, formulate, and solve engineering problems, and apply methods, skills, and modern engineering tools needed for engineering practice.

Interdisciplinary, new education standards and technologies, the digital classroom and online technologies, the relationship between engineering education and high-tech business and industry, models of digital competencies and ways to acquire them, the training of highly qualified staff, professional education in the school-university-enterprise system, and many other important aspects of modern engineering education are up for discussion right now [2].

Manufacturing enterprises in every industry are working in complex, fast-changing times, they are being challenged by an ever-shorter product life cycle, rising globalization, technological advances, and increasingly demanding customers in terms of product customizability and functionality. This is resulting in more and more complex products, systems, and processes, while the amount and complexity of the product information structure and flows are increasing.

In response to these challenges, a PLM approach has been developed, enabling integrated management of product-related information across its lifecycle, from conception to disposal. The PLM system is a set of consistent tools for integrating information about products and related processes throughout the entire product life cycle, enabling organizations to access and share information through business processes and improving operational efficiency. Furthermore, PLM is becoming increasingly important in today's corporate world due to its ability to support the company's efforts to attain long-term competitiveness by balancing innovation, enhancing operational efficiency and flexibility on the one hand, and cost reduction on the other. Moreover, the successful implementation of the

PLM approach becomes of key importance for the growth and development of organizations today.

Operational and strategic excellence acquired via PLM implementation in many companies has initiated the strengthening of the PLM initiative in various sectors, while the IT market records a drastic growth in PLM technology investments. According to the reports of the CIMdata company [3], the global leader in the field of PLM consulting, the PLM software market is the fastest-growing IT market today, with a total investment value of $66,6 billion in 2022 and an estimated growth rate of 10.1% over the following five years.

Despite this, companies are still struggling with the difficult implementation and attainment of PLM maturity, as a result of which the implemented PLM technologies usually fail to generate the expected business value. Johansson et al. [4] estimate that 70% of PLM implementation projects fail to achieve the expected goals, Singh et al. [5] also report an alarmingly low success rate for launched PLM initiatives.

Despite continuous conceptual and technological advancements, it appears that the PLM concept has not yet attained the anticipated maturity in industrial systems practice. Some of the key reasons for that are complexity and insufficient complexity and insufficient understanding of PLM as a business paradigm and technological concept, unstructured information flows, neglecting the business system's readiness for the introduction of PLM technologies, non-standardized and insufficiently formally defined processes, and inconsistency between the specific organization's needs and the functional aspects of the implemented PLM system [6, 7, 8].

However, most PLM implementation and institutionalization challenges are connected to the human factor. As Singh et al. [5] highlight, the success of PLM implementation hinges on the end users' acceptance and their learning curve. Furthermore, the adoption of PLM necessitates fundamental changes in the context of work practices and organizational culture. Furthermore, employees assume the role of change agents in PLM transformation processes, as well as key organizational levers in the launch and execution of PLM initiative. Despite this, various empirical studies report that the role and influence of employees in PLM initiatives are often underestimated.

Companies need employees to have a basic understanding of PLM concepts and be able to work efficiently and autonomously in a PLM environment. Future engineers not only need to have a comprehensive understanding and in-depth knowledge of the complex product life cycle but also the ability to collaborate and communicate effectively in interdisciplinary teams. Gandhi [9] indicate the need for establishing PLM education pertinent to industry demands. Greaves [10] emphasizes the necessity of establishing educational processes about PLM strategy, processes, and tools from the early stages of university education.

New labor market demands, shaped by rapid PLM evolution, require a shift in current engineering education to adapt to new realities and better prepare engineers for PLM. According to Burchardt [11] there is no systematic introduction of students to the field of PLM knowledge, and numerous empirical studies have supported this claim, indicating that PLM topics are not acknowledged as being part of contemporary educational paradigms.

This paper aims to provide a comprehensive review concerning the state of the art in PLM education; it discusses the topical issues of PLM education and possible future trends and developments. The paper attempts to increase awareness of the importance of PLM education development and encourage active debate about potential actions as responses to current issues.

The rest of the paper is organized as follows: The second section discusses the theoretical basics of the PLM concept; the third section provides an overview of previous research in the field of PLM education with the intention of defining the state of the art in PLM education; and the fourth section discusses future trends in the conceptual and technological development of PLM and their implications for future directions of PLM education.

The final section offers some conclusions and insights on additional considerations that future PLM education will have to take into account.

2. PRODUCT LIFECYCLE MANAGEMENT CONCEPT

PLM has emerged and developed under the influence of technological advances, new industry initiatives, and business paradigms. It is an IT-driven business model based on establishing the synergy between people and systems for processing information and synchronizing various processes throughout the entire product life cycle in order to optimize current and future products and related services.

Despite the prevailing narrative, PLM is much more than a technology solution, information system, or IT-based concept of integrated management of product information throughout the lifecycle. In attempts to conceptualize and formally describe PLM, terms such as "strategic business approach," "business model," "business paradigm," and "approach to management and optimization of business processes" have frequently been used, indicating the much broader context of PLM and the multi-layered nature of this phenomenon.

According to CIMdata [12], PLM is a business approach that applies a consistent set of business solutions to support the collaborative creation, management, sharing, and use of product information across a company.

As a technology solution, PLM facilitates the flow of information through the various phases of the product life cycle, acting as an integration core that connects automation islands. The essential PLM's function, according to Corallo et al. [13] is to provide a unique, time-limited source of product information, ensuring its consistency, traceability, and long-term archiving. The PLM system encompasses integrated information systems that unite various industrial software, including tools for creating, analyzing, simulating, and documenting product definition information, tools for collaborative product definition management, and digital manufacturing systems.

PLM unifies the domains of requirements management, product planning, production planning and realization, distribution and sale, customer service, delaying, and reusing products and their parts, thus creating a business environment for the integrated management of product information within organizational boundaries and through the inter-organizational value chain [13].

2.1 The necessity of PLM

The PLM concept has emerged as a response to the challenges posed by globalization, rapid technological progress, and the ever-shortening life cycle of products. It provides a paradigmatic model of how to maintain business efficiency and effectiveness in the face of current business challenges, which includes.

- Globalization's intensifying process has altered business conditions.
- Product complexity growth.
- Smart, connected systems are transforming the idea of a "product as an independent entity".
- Change the production strategy from "make-to-stock" to "mass customization."
- The trend toward outsourcing is leading to increasingly complex inter-organizational supply chains.
- Tendencies of production system digitization.
- Services that encompass the entire life cycle of the product are provided.
- Concurrent engineering, as well as related concepts.

PLM has evolved from specialized IT tools for automating specific business functions to digitally connected platforms capable of managing digital threads, and as Wang et al. [14] state, they continuously integrate new technologies related to the collection and processing of product information, the management of customer preferences and behavior, and the optimization of business workflows and processes.

The PLM implementation brings improvements in various aspects, both at the operational and strategic levels, generating growth in product profitability, growth in market share, greater user satisfaction, promotion of innovation, and so on.

The implementation of PLM generates business values through its capabilities to:

- Accelerate the exchange of information between processes within the product life cycle.
- Eliminate organizational barriers and foster cooperation throughout the inter-organizational value chain.
- Facilitate product knowledge management;
- Support the production of customized products;
- Increase workplace productivity;
- Reduce product life cycle costs;
- Reduce the time to market;
- Enhance the economic efficiency and flexibility of supply chains.
- Facilitate handling the product complexities;
- Support multidisciplinary interactions during product development and realization.

3. PLM EDUCATION – THE STATE OF ART

Emphasizing the relevance of the PLM concept for modern business systems growth and development, Greaves [10] stresses the necessity of establishing educational processes for PLM strategy, processes, and tools in the early stages of university education. He also stresses the need for establishing relevant pedagogical approaches in PLM professionals' education that shift learning concepts from studying the process to mastering PLM practice and understanding PLM strategy instead of becoming familiar with available PLM tools.

Burchardt [11] notes that students are not systematically introduced to the field of PLM knowledge; in addition, PLM education is not acknowledged as a part of contemporary educational paradigms, as is confirmed by numerous empirical studies. Current studies primarily focus on finding solutions to operational application problems, while the issue of developing comprehensive PLM educational paradigms receives insufficient attention.

It is believed that systematic PLM education is essential to successful PLM implementation in any industry. Moreover, Gandhi [9] indicates that PLM education can help improve product development competencies, skills to apply advanced product design tools, product base management competencies, industrial application to improve customer satisfaction, and maintenance and management of PLM processes.

Accordingly, there is an imperative to revise the existing engineering education curricula in order to ensure that students acquire the relevant multidisciplinary competencies required to work in a PLM environment, maximize understanding of PLM concepts, and gain practical "real-world" knowledge.

Over the past decade, different researchers have discussed the theme of PLM education in many contexts and subject areas. Most of them have focused on defining PLM-oriented curriculums, identifying teaching strategies used to increase PLM literacy, and discovering challenges and constraints that occur during PLM education development and delivery, as well as what strategies are used to overcome these obstacles. Furthermore, some studies have aimed to provide a model, an example, and suggestions for establishing and fostering meaningful partnerships to build authentic and relevant PLM experiences.

We reviewed and analyzed the research articles in the field of PLM education from 2014 to 2023. The following were some popular topics covered in these papers:

- Recognizing PLM education challenges
- Discussions on the contribution of PLM education to engineers' professional development
- Identifying appropriate PLM education approaches and designing new educational strategies and frameworks
- Development of a PLM-oriented academic course
- Creation of PLM educational resources

The table provides a summary of studies in the field of PLM education, along with their respective study goals.

Table1. *Overview of research in the field of PLM education*

Research aim	Focus on	Reference
Creation of the scenario around a product in its eco-system using simple technologies, in the way that all relevant organizational aspects, processes, and IT tools are present as they are in the real world.	Educational approach	[15]
Establishing the appropriate educational approach in engineering management, industrial engineering, and systems engineering programs on the PLM concept.	Educational approach	[16]
Design of a new course focuses on acquiring skills in customizing PLM systems to meet business requirements, incorporating fundamental aspects of PLM business models and engineering relationships.	PLM-oriented academic course	[17]
Consideration of the impact of the incorporation of PLM training in coursework and education of best practices, processes, and solutions at educational institutions as well as organizations on leveraging their intellectual assets and turning them into deliverable assets.	Contribution of PLM education to engineers' professional development	[9]
Describing the process of identifying and assessing the benefits of PLM applications that facilitate collaborative practices in project development and assessing their appropriateness within a higher education context.	Contribution of PLM education to engineers' professional development	[18]
Considering how foregrounding pedagogy will help realize the transformational potential of PLM through the skills and knowledge of the upcoming generation.	Contribution of PLM education to engineers' professional development	[19]
Analysis of existing approaches to solving the challenge of building a PLM professional education at the university in an industry context to educate industry employees, and improve engineering education at the university by using industry best practices.	PLM education challenges	[11]
Establishing the educational framework for the Bachelor, Master, and PhD study programs in industrial engineering and management, ensuring sustainable management of the product throughout its entire life cycle in a digital factory.	Educational framework	[20]
Establishing a new framework for global PLM strategy and a new curriculum for cultivating the "Global-PLM Producer" educational programs for undergraduate and adult education.	PLM education strategy	[21]
Considering the challenges in building the PLM competence of management students and outlining new opportunities.	PLM education challenges	[22]
Developing the PLM education materials that fall into the categories of fundamental concepts, digital product development, non-graphical concepts, and graphical concepts, and exploring methods of sharing these materials with students via PLM software workshops.	PLM learning materials	[23]

3.1 The concept of PLM-oriented education

According to Van Til [16], the establishment of PLM education is based on several strategies, including 1) incorporating PLM techniques and technologies into current courses; 2) establishing training programs for industry-relevant PLM software; and 3) developing a PLM dual education program with industry. On the other side, Burchardt [11] outlines three significant aspects of PLM education: 1) knowledge as an invariant core with an outer layer of empirical knowledge about specific systems with a tendency for constant development; 2) know-how, which refers to the development of the ability to transfer knowledge into the employee's working practice; and 3) modeling an employee's individual character through personality development training and mentoring.

The articles devoted to PLM education mostly focus on defining a set of competencies and learning outcomes for PLM-oriented educational programs. There is a consensus that PLM education should focus on cultivating professionals with multidisciplinary competencies rather than individual specialization in particular fields. The priority is to expand the scope of PLM education beyond its traditional engineering focus to include other business domains where the PLM approach has a significant impact. Additionally, educational processes must go beyond simply processing PLM theoretical assumptions and principles. Namely, the consistent application and control of the PLM approach requires extensive analysis and understanding of information flows, business activities, specific methods, and concepts used in different phases of the product life cycle.

Burchardt [11] stresses the need for structured programs in PLM professional education. These programs should focus on developing a basic understanding of PLM topics to support specialized PLM processes, building the competencies required to successfully implement PLM concepts, and improving practical skills to establish the basic PLM functional aspects (configuration management, variant management, change management, and workflow management). Sahu & Panda [22] are adding the following to this list: development of technical and commercial awareness; acquiring interpersonal skills to empower staff in the PLM implementation processes, working with software tools for product conceptualization, creatng of digital models, designing and simulating product environments; and developing skills for leveraging virtual space's potential for collaboration. While Van Til [16] argues that improving educational frameworks for the acquisition of PLM competencies in the digital factory environment necessitates the incorporation of thematic units and modules from the following areas: 1) theoretical and system approach for PLM in a digital factory environment; 2) technological preparation and support for production in a digital factory environment; 3) design of production systems (processes) in a digital factory environment; and 4) planning and controlling production and information support in a digital factory environment.

Tamaki et al. [21] define a strategy for the development of so-called "global-PLM producer" education. The strategy defines the educational goals for the development of the comprehensive competence necessary to cultivate the global-PLM producer through the competence matrix.

This matrix delineates specific competencies for each phase of the product life cycle, including: 1) product strategy; 2) business model; 3) global market sensing and new product plan; 4) production architecture strategy; 5) supply chains management, manufacturing and quality control; 6) global marketing channels, sales and maintenance services. These stages are linked to four levels of business administration, which determine specific competencies for managing the internal and external organizational environment, including: 1) global business environment; 2) business creation; 3) customer creation; 4) product development and operational management.

Product lifecycle phase

PLM level	Product strategy	Business model	Global market sensing	Product architecture strategy	SCM, manufacturing and QC	Global marketing channel, sale and maintenance
LEVEL 1 Global business environment	Product line-up strategy Platform strategy Product line strategy Variation management					
LEVEL 2 Business creation		Analysis of business environment New business concept Global business model Competitive strategy				
LEVEL 3 Customer creation			Marketing research Market segment positioning Customer behavior analysis New product planning			Global logistic strategy Local market cultivation Local market promotion Local service promotion
LEVEL 4 Product development and Operational management				Technological benchmark Product specification Concept development System architecture design Integrated PLM business process model	Global framework building of production and SCM strategy Mass production planning Manufacturing process planning	

Figure 1. *„Global-PLM producer" competence matrix [21]*

As an important aspect of the PLM educational paradigm, many authors point to the imperative of establishing synergy between the academic sector and industry. This involves various modes of interaction between students, teachers, and industry experts, blurring the boundaries of conventional education and encouraging the realization of PLM's transformational potential through the skills and knowledge of future generations of engineers.

Burchardt [11] asserts that industrial systems play a significant role in the PLM educational paradigm, whose role is reflected in the critical analysis of curricula, the active involvement of experts in educational processes, and the provision of financial support to educational programs. Academic institutions play a crucial role in imparting invariant core knowledge, whereas industrial systems concentrate on teaching specific aspects of empirical knowledge, tools, and their applications, thereby integrating practical knowledge into educational processes. Van Til [16] also emphasizes the importance of more intensive interaction between educational institutions and industry and research centers.

Conlon [19] advocates for alternative approaches that align with foregrounding pedagogy in education, prioritizing student work in a practical PLM environment over the transmission of curriculum content. For instance, they recommend establishing PLM learning communities that provide both academic and theoretical knowledge as well as practical content, encouraging involvement from external stakeholders, while not neglecting the impact of academic and theoretical knowledge on the further development of critical practice.

This mainly refers to the establishment of PLM education partnerships with PLM technologies providers (PTC, WhichPLM, ITC, Infotech, etc.). These partnerships provide universities with resources, enable teachers to stay up to date with the latest technological advancements and current industry practices, while providing students with an in-depth understanding of industrial processes and practices, help in realizing correlations with other relevant areas of knowledge, and also encourage students to develop a critical perspective of existing practice.

With the intention of enabling students to learn and apply concepts in a simulated business environment, PLM software solutions can be used for educational purposes to create a simulation environment that mimics a real business environment.

4. FUTURE TRENDS IN PLM-ORIENTED EDUCATION

A new era in PLM's technological and conceptual evolution is on the horizon.

Today's companies face the challenge of developing more personalized, smarter, and eco-friendly products. According to [24] success necessitates continuous and, more rapid innovation in products and processes. Going forward, companies must undergo a digital transformation of their businesses and evolve their current product lifecycles to enable true end-to-end lifecycle optimization. Also, companies today must respond to the imperative of sustainability in order for society to tackle climate change and pollution problems.

According to CIMdata [25] research, which examines how important certain technologies, processes, or abilities are for making sustainability efforts, PLM is an important part of a systemic response. PLM-enabling solutions must act as a nexus for sustainability information attached to the digital thread as it evolves across the product lifecycle. Moreover, PLM must support a model of production and consumption that involves reusing, repairing, refurbishing and recycling existing materials and products as long as possible.

PLM is a critical component for fulfilling companies' digitalization strategies. The use of emerging technologies like the Internet of Things, cloud computing, big data, and artificial intelligence transforms PLM systems into digital platforms capable of supporting the digital transformation.

On the other hand, the technologies associated with Industry 4.0 provided potential solutions to the challenges that prevented mass adaptation of PLM in the past [26]. Thus, one of the key trends in the development of PLM in the future undoubtedly refers to the realization of an integrated PLM by application of key industry 4.0 technologies.

Ji & Abdoli [26] have identified the most important technology concepts brought forth by Industry 4.0 that can help companies set up better processes for managing all stages of the product lifecycle, including:

- Big data analytics, or data mining using artificial intelligence technologies;
- Data collection via cyber-physical systems or digital twins.

Today's PLM environment makes extensive use of artificial intelligence and machine learning technologies. The machine learning concept enables the automation of the time-consuming process of acquiring and even discovering knowledge that might otherwise be overlooked [27]. These technologies find application in various aspects of PLM. The manufacturing industry widely adopts these concepts for process monitoring and fault detection, and their predictive ability also extends to the field of predictive maintenance.

Tao et al. [28] defined digital twin as an integrated multi-scale and probabilistic simulation of a complex product or system to mirror the life of its corresponding twin. It is a bi-directional relationship between a physical artifact and the set of its virtual models, enabling the efficient execution of product design, manufacturing, servicing, and various other activities throughout the product life cycle [29].

In the context of PLM, digital twin technologies can be used as tools for the simulation, prediction and optimization of a physical production system or product [30] through different phases of its life cycle.

According to Pang et al. [31] some of the application areas of digital twin in the context of PLM include the detailed recording and storage of process data from manufacturing, the direct use of information on manufacturing errors and part defects to identify critical production steps, the ability to customize products to customers' needs, the scheduling of repair processes based on knowledge of the product's entire operating history throughout the product's life cycle, etc.

Today`s PLM systems need to be adapted to become more comprehensive product innovation platforms. As a set of "realistic product and production process models, DT links enormous amounts of data to fast simulation, which allows the early and efficient assessment of the consequences of the design decisions on products and production lines." [32] „These capabilities allow the enterprise to focus on innovating to create value, leveraging higher-level or more advanced product innovation platform capabilities to assess product and business scenarios to optimize the business." [33]

The foundation of digital twin creation is coordinated digital threads, which demand the storage, maintenance and integration of digital data about products and resources across all stages of the product life cycle, which relies on the use of technical concepts like MBE, MBSE, etc. for product and production environment modeling and validation.

MBE is an approach that uses mathematical multi-dimensional models as an integral part of the technical product definition and uses a single platform to support the requirements of analysis, design, implementation, and verification of a product throughout its lifecycle, beginning in the conceptual design phase and continuing throughout development and later lifecycle phases [32].

The MBSE approach allows groups of users to collaborate on a single system, where they can share data, simulate and visualize a highly detailed model of a future physical product, and exchange information in the form of a model instead of a document.

Considering the current trends in PLM conceptual and technological evolution, engineering education must incorporate some specific topics to prepare future engineers with the competencies to work in a PLM environment. This includes:

- The concept of Life Cycle assessment (LCA) and the potential of integrating LCA tools with PLM technologies for facilitating the incorporation of sustainability principles into product and process engineering;
- The possibilities of applying PLM-enable technologies to help engineers make critical decisions that will affect product sustainability, such as:
    - Designing with sustainable part and assembly reuse in mind
    - Designing for sustainable manufacture
    - Designing with a sustainable supply chain in mind
    - Considering how the product will be used and taking early steps to design the product to improve lifecycle sustainability.
- The concept of PLM-enabled digital transformation;
- Digital twin-enabling technologies and artificial intelligence, and the way they transform how the company operates and how it manages and leverages product information from concept until a product is retired.
- Engineering approaches that use multidimensional models as an integrated part of the technical product definition, such as the MBE and MBES approaches.

5. CONCLUSION

The converging impact of technological progress and new business paradigms has led to changes that have challenged every aspect of engineering education. To cope with these run-away changes, the educational system must prepare the workforce with the competencies to work in new industry environments.

PLM is essential to a systemic response to the challenges of developing more personalized, smarter, and eco-friendly products. Thus, PLM-oriented education needs to be at the core of contemporary engineering education paradigms.

Furthermore, as the PLM concept evolves, the body of comprehensive PLM competencies continues to change. The trend of incorporating new technological concepts into PLM has repercussions for how educational systems should prepare future engineers for work in a PLM environment, imposing new topics up for discussion.

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REFERENCES

[1] Passow, H. J., & Passow, C. H. (2017). What competencies should undergraduate engineering programs emphasize? A systematic review. *Journal of Engineering Education, 106*(3), 475-526.

[2] Galikhanov, M. F., Barabanova, S. V., & Kaibiyainen, A. A. (2021). Core trends in engineering education: five years of the "Synergy" international conference. *Higher Education in Russia, 30*(1), 101-114.

[3] CIMdata (2023). *Market analysis results, PLM market & industry forum*, CIMdata.

[4] Johansson, B., Andersson, J., Lindskog, E., Berglund, J., & Skoogh, A. (2013). Evaluation and calculation of dynamics in environmental impact assessment. *International Conference, APMS 2012, Rhodes, Greece,* 135-141. Springer Berlin Heidelberg.

[5] Singh, S., Misra, S. C., & Kumar, S. (2021). Institutionalization of product lifecycle management in manufacturing firms. *IEEE Transactions on Engineering Managemen*t.

[6] Soto-Acosta, P., Placer-Maruri, E. & Perez-Gonzalez, D. (2016) A case analysis of a product lifecycle information management framework for SMES. *International Journal of Information Management, 36*(2), 240–244.

[7] Plo, L., Robin, V., & Girard, P. (2016). Understanding PLM system concepts to facilitate its implementation in SME: the real case study of POULT. In *IFIP International Conference on Product Lifecycle Management,* 512-522. Springer, Cham.

[8] Eigner, M. (2021). *System lifecycle management.* Springer, Berlin, Heidelberg.

[9] Gandhi, P. (2014). Product lifecycle management in education: key to innovation in engineering and technology. In *Product Lifecycle Management for a Global Market: 11th IFIP WG 5.1 International Conference,* 121-128. Springer Berlin Heidelberg.

[10] Grieves, M. (2006). Product Lifecycle Management: driving the next generation of lean thinking. McGraw-Hill.

[11] Burchardt, C. (2015). Establishing product-lifecycle management education at university in industry context. In *2015 IEEE International Conference on Engineering, Technology and Innovation,* 1-7. IEEE.

[12] CIMdata (2005). *The high-end MCAD and cPDm market segments of the PLM industry*, CIMdata.

[13] Corallo, A., Latino, M. E., Lazoi, M., Lettera, S., Marra, M., & Verardi, S. (2013). Defining product lifecycle management: A journey across features, definitions, and concepts. *International Scholarly Research Notices,* 2013.

[14] Wang, Z. L., Liu, H. C., Xu, J. Y., & Ping, Y. J. (2021). A new method for quality function deployment using double hierarchy hesitant fuzzy linguistic term sets and axiomatic design approach. *Quality Engineering, 33*(3), 511-522.

[15] Fradl, B., Sohrweide, A., & Nyffenegger, F. (2017). PLM in education–the escape from boredom. In *Product Lifecycle Management and the Industry of the Future: 14th IFIP WG 5.1 International Conference,* 297-307.

[16] Van Til, R. (2019). Integrating PLM into engineering education: PLM case study. *Product Lifecycle Management*: *Case Studies,* 21-27.

[17] Padillo, A., Racero, J., Molina, J. C., & Eguía, I. (2018). PLM for education. The next generation of engineers. In *Product Lifecycle Management to Support Industry 4.0: 15th IFIP WG 5.1 International Conference,* 327-337. Springer International Publishing.

[18] Vila, C., Ugarte, D., Ríos, J., & Abellán, J. V. (2017). Project-based collaborative engineering learning to develop Industry 4.0 skills within a PLM framework. *Procedia Manufacturing, 13,* 1269-1276.

[19] Conlon, J. (2021). Foregrounding pedagogy in PLM implementations in higher education: A case study from the UK. In *IFIP International Conference on Product Lifecycle Management,* 341-352. Cham: Springer International Publishing.

[20] Edl, M. (2013). Educational framework of product lifecycle management issues for master and PhD study programmes. In *Advances in Production Management Systems*, Greece, 614-621. Springer Berlin.

[21] Tamaki, K. Y., Park, Y. W., Abe, T., & Goto, S. Development of educational programs for global-PLM producer through action project group activities by industry-university cooperation.

[22] Sahu, K., & Panda, B. P. The challenge of teaching PLM to Management Students: A KIIT-DS PLM case study. *Marketing*, 5, 522.

[23] Procopio, D., Morris, J., & Wagner, J. R. (2023). Application of product lifecycle management in the University classroom and laboratory. *In 2023 ASEE Annual Conference & Exposition*. Baltimore Convention Center.

[24] CIMdata (2020). *Modernization of PLM––accelerating innovation*, CIMdata

[25] CIMdata (2022). *Sustainability and PLM,* CIMdata

[26] Ji, X., & Abdoli, S. (2023). Challenges and opportunities in Product Life Cycle Management in the context of Industry 4.0. *Procedia CIRP, 119*, 29-34.

[27] Pham, D. T., & Afify, A. A. (2005). Machine-learning techniques and their applications in manufacturing. Proceedings of the *Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 219*(5), 395-412.

[28] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology, 94*, 3563-3576.

[29] Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin

for design and production engineering. *CIRP Annals, 66*(1), 141-144.

[30] Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., & Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing, 61*, 101837.

[31] Pang, J., Huang, Y., Xie, Z., Li, J., & Cai, Z. (2021). Collaborative city digital twin for the COVID-19 pandemic: A federated learning solution. *Tsinghua Science and Technology, 26*(5), 759-771.

[32] CIMdata (2017). *Achieving the most from Model Based Enterprise implementations,* CIMdata.

[33] Tata Technologies (2018). *MBSE-PLM alignment to support industry 4.0 and IIOT*, Tata Technologeis.