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Procedia CIRP 107 (2022) 1226–1231

www.elsevier.com/locate/procedia

55th CIRP Conference on Manufacturing Systems

Reconfigurable Pilot Lines Enabling Industry Digitalization: An Approach for Transforming Industry and Academia Needs to Requirements Specifications

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Abstract

Reconfigurable Pilot Lines (RPLs) are one practical concept for implementing the test-before-invest strategy to improve skills and capabilities of European small and medium enterprises (SMEs). SMEs typically have limited resources for systematically exploring the potential benefits of available technologies. By utilizing the RPLs offered by research institutes and universities, companies can get both commercially uncommitted and realistic proof-of-concept studies for their applications, and valuable information about the skills and personnel competences needed for successful implementation of the new technologies. Test-before-invest services offered by RPLs can also foster the process of adopting new digital technologies in manufacturing industry. RPLs are versatile. RPL can act as a test bed for manufacturing company's investment study, industry-scale product development laboratory for technology provider, as well as a platform for scientific research and education. Due to versatile roles and functions, defining pilot line requirements specifications call for systematic contribution from both industry and academia. This paper introduces a collaborative approach for defining requirements specifications for RPLs from the future technology skills development perspective. As a basis for this research, we combine results of three joined industry-academia workshops and one academic workshop with total 87 participants utilizing Affinity Wall method. This data was supplemented with an online survey for 74 companies from manufacturing industry. The analysis indicates that defining requirements specifications and development roadmaps for RPLs is a complex process, requiring multidisciplinary collaboration. Based on the analysis, a conceptual model supporting the requirements specification work is proposed in this paper. The model was applied to an existing testbed environment for further evaluation.

Keywords: Pilot Lines; Industry 4.0; Robotics; Automation

1. Introduction

Digital transformation (DT) has irrevocably shaped the future landscape of manufacturing industry. Starting from digitization of analog data and processes, it acts as a backbone to the ongoing 4th Industrial Revolution [1]. Due to its great potential on improving resource efficiency and competences of the industry in several ways, including product engineering, marketing and customer involvement [2][3], it is essential to support the progress of digital transformation within the whole variety of industrial companies in different sectors and throughout the manufacturing value chain. At European level, Strategic Innovation Agenda work carried out on main platforms and programs emphasize the need for joint activities and university-industry collaboration to ensure the successful implementation of ever-growing number of new technologies

10.1016/j.procir.2022.05.136

boosting competitiveness, sustainability, resilience, and human centricity of European industry [4][5].

One approach to support manufacturing companies to speed up with the digital transformation are different learning and teaching environments provided by the higher education institutions (HEIs) and research institutes. Environments like Learning Factories (LF) and Teaching Factories (TC) have a long history on developing skills for new industry workforce, especially for students aiming towards a degree [6][7].

Today, the accelerating speed of digital transformation places new requirements for continuous education of people already in working life. The same reason is behind the pressure for the research to introduce new demonstrations and research setups with minimum ramp-up time. Advanced technologies in manufacturing, especially ones related to robotics and automation, are often regulated to avoid hazards included, which can discourage companies to start experiments with those technologies. There is a need for specified testbeds and experiment areas which can offer easy access opportunities for companies to familiarize themselves with the possibilities of latest technical innovations [8].

Reconfigurable Pilot Lines bring their contribution to the issue. In contrast to education-focused LFs [9], RPLs primary objective is to act as research-oriented test-before-invest environments, enabling quick and efficient way to introduce new technologies and knowledge about their potential applications to industry. Pre-defined and systematic reconfigurability makes these environments more flexible than standard university and research institution laboratories, and thus faster on reacting on industry needs. This paper will outline the key characteristics to be considered when building a successful RPL, meeting the needs from both industry and academia. RPLs possibilities in developing skills and competences related to key digital technologies is also discussed.

This paper is organized in five sections. In the next section, RPLs opportunities in supporting digitalization of manufacturing, relevant key technologies as well as the skills enabling digital transformation in manufacturing industry are introduced. Third section describes the material and methods of this research, and fourth section presents the results. Lastly, in section five, key findings are discussed, and future research pathways are initiated.

2. RPLs supporting digitalization of manufacturing industry

Especially SMEs generally have limited resources available for research and development activities. The early stages of the digital transition require not only technical capabilities but also a mind-set shifting [10]. Previous research has identified several skills and knowledge domains that are essential for efficient implementation of digitalization technologies. General understanding of algorithms, systems theory and ICT systems as well as problem solving skills and creativity are among the ones seen important [11]. Skills cap is not just an issue of individuals lacking the specific training or education. Also, companies must be able to identify and choose the fitting technologies for their business at the organizational level [12]. To overcome these barriers of progress, SME's need both information about the key enabling technologies (KETs) of digitalization, as well as understanding and vision about the business potential of new technologies in their company specific operation environment. Accessible support for boosting the digitalization is especially important for European SMEs, due to characteristics of their typical production types and programs. Mass production of simple products is less likely to happen in Europe, and back shoring of production is more probable with complex low volume products [13]. Importance of digital operations in manufacturing chain grow together with product and production complexity [14].

In recent years, several publications have discussed about advanced technologies and KETs of digitalization and Industry 4.0. European Union describes advanced technologies as technologies supporting the transition towards low-carbon and knowledge-based economy. These include advanced manufacturing technology, advanced materials, artificial intelligence, augmented and virtual reality, big data, blockchain, cloud computing, connectivity, industrial biotechnology, internet of things, micro- and nanoelectronics, mobility, nanotechnology, photonics, robotics and security [15]. From the manufacturing industry's point of view the relevance of these technologies varies, but the extensiveness of the list shows that there are several discrete technologies available, which require specific skills to implement them.

Previous papers have introduced technologies and applications relevant for RPL development. Virtual reality (VR) is showing high potential for taking the safety training in manufacturing cells to new level of flexibility [16]. In conjunction with digital twin of the system, it enables remote safety training for large groups of people simultaneously. Extended reality (XR) technologies in general can support human-robot collaboration in several lifecycle phases like design, commissioning, and operation [17]. XR technologies play also important role in implementation of Cyber-Physical Systems (CPS). When connected and supplemented with other technologies, like gesture and voice controls, human-machine collaboration can become personalized for each operator [18].

In operations like robotized machining or welding, flexible fixturing of workpieces is an essential enabler for cost-effective operations when lot sizes are small. Latest research show that hexapod based technologies can bring new advantages by utilizing invert kinematics [19]. This approach saves computation time, which again supports shorter setup times and tendency to lot size one.

Flexible, re-usable and modular robot programming is another issue limiting the growth in robot installations in manufacturing industry. New approaches supporting the operator in modifying the robot movements and activities without coding are developing fast. One recent concept utilizes Action Data Tables (ADT) in automatic generation of robot code previously not executed in the system [20]. This approach is interesting for RPLs due to its lightweight approach compared to natural language processing. It can significantly improve robot cell setup time and thus enable shorter production series to be successfully robotized, even in companies lacking experience on robot programming.

3. Research material and methods

Methods used in this research consisted of expert workshops for research material collection and Affinity Wall Mapping for sorting and classification of the data collected from these workshops. Workshops were executed online, and participants gave their answers by writing notes on digital platform. All questions were open-ended. The second data collection method was an online survey conducted by BSc students working in local companies. A case study is conducted to further evaluate the model.

3.1. Research material collected from Workshops and Affinity Mapping Analysis

The workshop series consisted of four workshops. First, three workshops were arranged as thematic workshops in industry-academia collaboration. All of them targeted on collecting needs and expectations regarding the digitalization of the manufacturing industry. Workshop themes were selected to focus the discussions and collaboration on key elements of the industry digitalization. The themes were:

- RDI environments and education
- Robotics and automation / human-robot collaboration
- Data-based service creation in industrial ecosystems

Concerning each workshop's theme, participants were asked to describe the future from their company's perspective in four categories: Operating environment, Research and development, Resources and Skills and Education. This phase was executed twice, first targeting to year 2025 and next with target year 2035. Totally 72 participants joined workshops one to three.

To foster the analysis of the data collected in the workshops one to three, all input notes were manually transferred to a single digital platform to form a common Affinity Wall. The input data was not mixed between themes and categories. A working group of researchers conducted an analysis of the data by forming an Affinity Diagram with clustered input notes and formulated headers for clusters with commonalities.

Workshop four was organized for academia representatives only and were focused on researchers views on RPLs role in future competence and skills building. There were totally 15 participants in this workshop. The following questions were presented to participants:

- What are the key elements of a successful Reconfigurable Pilot Line (RPL)?
- What are the key properties of the RPL from the skills building point of view?
- What are the key skills and competences RPLs should provide for the target audience?
- What are the key properties of the RPL from the research point of view?
- What are the key research themes RPL should support?
- What needs to be demonstrated to industry with RPLs by 2025?
- What needs to be demonstrated to industry with RPLs by 2035?

Similar analysis was conducted for the output of the workshop four as for the outputs for workshops one to three, except that now a pair of researchers accomplished the analysis.

3.1.1. Outcomes of the workshops

The total amount of participants for the workshops one to three workshops was 72, and it consisted of people academia, higher education institutes and companies. In workshop four 15 representatives of academia were participating. Table 1 shows the distribution of participants between workshops and the number of notes created in the workshop phases analyzed in this research.

Table 1. Outputs of the workshops

Workshop	Number of participants	Notes created
1. RDI environments and education	12	37
2. Robotics and automation / human-robot collaboration	32	70
3. Data-based service creation in industrial ecosystems	28	64
4.RPLs as a future RDI platforms	15	161

According to the analysis, outputs from the workshops one to three indicates that automation, data and digitalization are common subjects that affect the operating environment of companies. This was a shared scene between all three workshops. Platforms and ecosystems as well as resilience and manufacturing location considerations were also seen notably important, as these raised up in two of three sessions.

When analysing the advanced technologies, robotics and AI and their implementation were the most often mentioned themes in the data. Need for collaboration between domains and actors on different fields of industry and academia can also be recognized as a shared interest, especially in R&D activities and resource sharing. Lifelong learning and shortage of manpower raised up as a concern as well, as it was also an issue identified in all three workshops.

Workshop four, carried out by academia representatives only, raised customer orientation and community building as general success factors for RPLs. Abilities on creating linkages between technology and business was seen as a comprehensive skillset that RPLs should offer for their target audience, and the skills building for people with varying knowledge and skills gaps was seen important as well. Mentioned integration to industry was as well one of the key properties of the RPLs from the research point of view, together with flexibility, easy utilization, and clear and well-defined data management policies. Numbers of digital technologies were mentioned in the data related to RPL's support to research themes and thing RPLs should be able to demonstrate in the future. Anyway, no single technology raised significantly above others. Sustainability aspects instead can be identified as one domain considered important, as it was one of the main research theme RPLs should support according to researchers.

3.2. Online survey analysis

The online survey question analyzed in this research was:

- What technological competencies (skill and capabilities) does your company need in the future, starting form year 2023 for five years ahead?

Question was a multiple-choice question on a five-point scale, one corresponding to "Not at all" and five to "Very much". The digital tools, application areas and technologies referred in question are presented in table 2.

Table 2. Digital tools, application areas and technologies enquired in the survey

Digital tools	Application areas	Technologies
Digital Twin	3D printing	5G-connectivity
Simulation	Robotics	Cybersecurity
VR/AR/XR - technologies	Cobotics	Industry 4.0
Digital design and optimization	Flexible manufacturing	Industrial Internet of Things
Model based design	Human-machine collaboration	Edge computing
		High power computing
		Cloud service
		Big data
		Machine learning / AI

The survey was distributed to industry trough engineering students training reporting process. On summer 2021, approximately 200 Mechanical Engineering students were asked to deliver the online survey link to the company they were performing their mandatory summer training. In this research, only the data from manufacturing industry companies was considered. 74 answers matching the criteria above were received in the timeframe of this research work. 29 of the answers were from SMEs, and 45 from large companies. Survey data was analysed by calculating the frequency of each available answer option for each question separately. Data was categorized by company sizes, so that SMEs were separated from large companies. This research didn't include comprehensive statistical analysis for the survey data. Therefore, analysis of the data is considered as indicative within the context of this study.

Online survey collected indicative data about the technological competence's companies consider needed for them within five years ahead starting from 2023. Table 2 presents the five most important technologies from the company's point of view. In the analysis, answers "Very much" (5 on scale 1-5) and "Much" (4 on scale 1-5) were considered as "Important" and reported together. The survey indicates that the SMEs are expecting investments and future R&D efforts in both digital transformation side and to the hardware side.

Table 3. Five most important technologies according to the survey.

Technology	Important to, percentage of answers
Cybersecurity	63%
Robotics	57%
Human-machine collaboration	56%
Flexible manufacturing	55%
Digital design and optimization	55%

Overall, seven of the 19 mentioned technologies were considered as "important" for 50% - 70% of the companies, seven for 30% - 50% of the companies and five for less than 30% of the companies.

3.3. Case study: FieldLab

Tampere University of Applied Sciences (TAMK) significantly renewed its mechanical engineering laboratory environments during years 2018-2019. In 2018, TAMK applied for funding from Finnish Ministry of Education and Culture for profiling in Industry 4.0. During the project new industrial automation and ICT skills and assets were acquired, including mobile robotics, cobots, and a large-scale robotized 3D-printing environment.

Current testbed offers modern facilities for education, research and industry R&D at the area of robotics and data collection and visualization. Future objective is to convert the environment into a Reconfigurable Pilot Line. Two separate topics for Pilot Lines are already identified, namely, Industry 4.0 and additive manufacturing. The research work presented in this paper uses robotized large-scale additive manufacturing (LSAM) environment as a case study and reflects the results of the workshops and survey to the development plan of this pilot line. LSAM is a fruitful environment for development plan. The full-scale printing of a large object is a complex process where several KETs such as advanced robotics, cobotics, material technology, digital design and optimization, model-based design and simulation are required [21][22]. Further, in LSAM it is plausible to utilize a variety of other key enabling technologies such as digital twins [23], making it an interesting platform for a development plan case study.

4. Results

Analysis of the research data highlights the diverse expectations and requirements set to RPLs. Emerging manufacturing technologies and research activities around them are at the core of the RPLs, but there are several aspects to be covered during the development work. Figure 1 illustrates major domains to be considered when defining the requirements specifications to Reconfigurable Pilot Line.

There are several key enabling technologies of digitalization, which can be combined to almost any RPL. For example, Pilot Line of Mobile Robotics may act as a platform for data analytics research and demonstrations. Findings of the Affinity Analysis as well as from the online survey indicate that there is a demand for these kinds of activities. Adding new technologies and elements beside the core technology of the RPL adds the complexity of the system. This needs to be considered when evaluating the reconfigurability of the system and feasibility of integrating additional KETs to RPL. Further research around the topic is needed to formulate detailed model between the integrated KETs and reconfigurability of RPL.

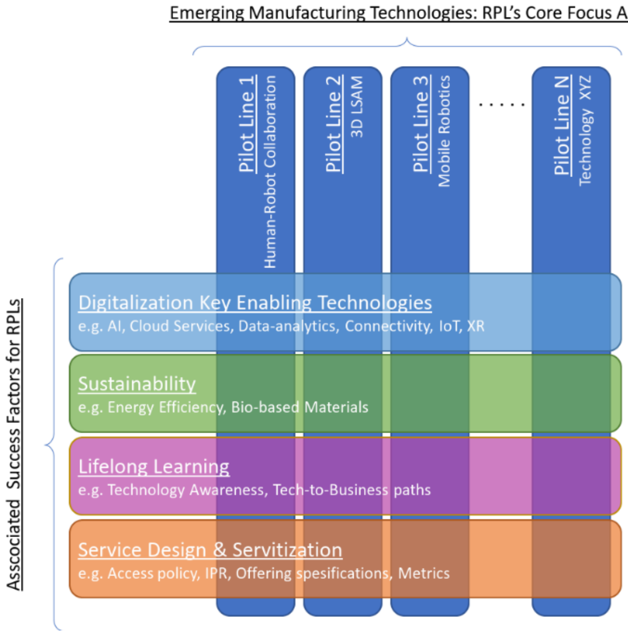

Fig. 1 Interaction of RPL's core focus areas and associated success factors

Lifelong learning was raised up as a need from industry side, and academia emphasized the connection of technical skills building and business perspectives. This sets requirements to the way how proof-of-concepts and technology demonstrations are arranged in RPLs. While raising awareness about the latest technology is valuable as such, the business objectives should be brought up systematically in the early stages as well. It is proposed that data-enabled metrics should be a future research topic around RPLs, targeting to accelerate the transition from proof-of-concepts towards proof-of-values.

Sustainability plays ever greater role when companies analyze their future operating environments. In this research, the theme was found a common interest for both industry and academia. Considering the discussion in recent years, it is a domain to consider when considering RPL's development roadmaps.

4.1. Case study results: TAMK FieldLab development plan

Results of this research were used to formulate a development plan for TAMK FieldLab, in order to accelerate its transition into a Reconfigurable Pilot Line. Core focus area of the RPL is robotized LSAM, which in practice means the ability to print a variety of large objects utilizing several technologies identified in the results of the workshops and the survey. The development plan relates to success factors illustrated in Fig. 1.

The opportunities that robotized LSAM offers for integrating associated digital key enabling technologies should be utilized in versatile ways. As an example, data-analytics and machine learning capabilities should be elaborated to the level where they can be utilized not only for serving the LSAM related activities but also as integrated but independent RDI platforms. Cybersecurity should be considered similarly; research and development activities should be made possible also to personnel not familiar with LSAM. XR-based cyber-physical environments and their applications as well as digital twins are also potential topics to integrate with LSAM Pilot Line, since they enhance the operational effectiveness of "lot size one" production, typical to LSAM.

As a process of additive manufacturing, LSAM is potential objective for reducing material consumption by topological optimization. Bio-based materials are another field of expertise enabling LSAM Pilot Line's activities supporting sustainability aspects. Better knowledge of AM-process details, like bonding of layers and printing orientation relation to product strength also has direct influence on material consumption. Recyclability of printing materials and the process for re-grinding the scrapped products into new raw material is essential topic for sustainability research and the RPL should be targeted to support this work.

LSAM Pilot Line can enhance its support for lifelong learning in several ways. Research results indicate the need for better integration of business objectives into activities of raising technological awareness. This can be improved by taking the productization and investment cost analysis, as well as lifetime costs, into systematic consideration during any technological demonstrations. This should apply also to any other lifelong learning related development tasks, like formulation of modular micro credits supporting both degree studies and continuing education of people already in work life.

Integration to industry and ease of access can be improved by servitization and service design of RPL offering. It is an important activity affecting directly to their potential to meet the European level goals set to them. Especially SMEs are not utilizing this offering up to its full potential. It is essential that Pilot Lines and other RDI environments formulate a national level access policy and share their resources on making the offering and value proposition better visible to industry. FieldLab LSAM Pilot Line should be integrated to national initiatives around the topic.

5. Conclusion

This paper introduced results from expert workshops and online survey conducted for the companies regarding the future technologies. The paper uses this material as to formulate new implementations for the current system in order to transform the FieldLab to a Reconfigurable Pilot Line envisioned in the introduction.

Research data included several key enabling technologies of digitalization, raised up strongly both in the workshops and in the online survey. Results suggest that KETs generally are seen as necessary part of RPLs. However, only indicative analysis about the importance of each KET can be done within this research since a comprehensive statistical analysis would give more reliable results. In the future, further research will be done to attain better understanding about the process and reasoning how companies select the technologies they emphasize in their implementation plans.

Despite careful and explicit work on this research, some limitations exist. Online survey data was not analyzed statistically, so results shall be considered indicative only. In the workshops, the theme and ancillary program like keynote presentations topics may have affected on which industries and backgrounds the participants represent.

Acknowledgements

This research was funded by Academy of Finland within project "Sustainable Industry Ecosystem", Decision number: 337722.

CRediT author statement

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Mika Ijas: Methodology, Formal analysis
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