Advances in Manufacturing Technology XXXVI
A. Thomas et al. (Eds.)

doi:10.3233/ATDE230908

Design of a Demonstrator Environment for Investigating Multi-Factory Production and Operation Challenges

Sam Brooks[a,1,2], Duncan McFarlane[a], Alan Thorne[a], Zhengyang Ling[a], Gregory Hawkridge[a], Darius Danaei[a], Sławomir Tadeja[a], Svetan Ratchev[b], Sudhir Rama Murthy[a], Nikolai Kazantsev[a], Sebastian Pattinson[a], Chander Velu[a], and Thomas Bohné[a]

[a] *Institute for Manufacturing, University of Cambridge, Cambridge, CB3 0FS, UK*
[b] *Institute for Advanced Manufacturing, University of Nottingham, Nottingham, NG8 1BB, UK*

Abstract. Demonstrators, testbeds and learning factories enable researchers to investigate important manufacturing challenges and to trial solutions without disrupting industrial production facilities. In this way, solutions and systems can be developed close to a 'production-ready' state prior to industrial deployment. This paper reviews demonstrators and testbeds developed for smart manufacturing in the last 20 years. A key observation is that such demonstrators have predominantly focused on emulating single or multiple closely connected operations. Such developments reflect the activities of a single production facility and/or organisation. In contrast, there are few reports on demonstrators which seek to replicate the behaviour and challenges associated with multi-site factories or integration with existing legacy factory systems. To address this gap, a multi-operation demonstrator has been created. The demonstrator aims to replicate coordinated production between multiple small manufacturing sites and provides a testbed to investigate operational challenges. The current demonstrator, the research investigated, and the direction of future research proposed are outlined.

Keywords. Manufacturing, Multiple Sites, Demonstrator, Connected Factory, Industry 4.0.

1. Introduction

Manufacturers are facing increased challenges, with supply chain disruption, which has continued beyond the COVID-19 pandemic, increased energy costs, variation in demand and a shortage of labour and skills [1]. New technologies are frequently highlighted as a solution to these problems. For example, advanced IoT sensors can give a company information about variation in the quality of products. However, if this is not communicated to customers, it cannot be utilised effectively during assembly or further processing [2]. As this example highlights, these problems occur not at a single company or site but across multiple sectors and locations. Therefore, manufacturing research must

---

[1] Corresponding Author: Sam Brooks, sjb351@cam.ac.uk, dr.s.brooks@hotmail.com
[2] Work conducted as part of the EPSRC/Innovate UK funded project: Made Smarter Connected Factories Centre EP/V062123/1

consider multiple interacting companies and organisations and their communication. Figure 1 gives an overview of some of the challenges of communicating and coordinating between factories within a supply chain.

Testing solutions to challenges can help manufacturers prepare and recover quickly; however, testing on critical systems such as production lines in operation is disruptive and expensive. Therefore, researchers often utilise demonstration or testbed factories to enable research [3]. This is common in many industries dealing with critical infrastructure, such as transport, communication networks, manufacturing and utility infrastructure research [4]. This paper reviews existing demonstrators and testbeds used in research. Information gathered has been used to inform the design of a new multi-factory demonstrator, which facilitates research across multiple factories. The demonstrator aims to address many of the shortcomings of current demonstrators and testbeds.

The term demonstrator is used in this paper to encompass terms demonstrators, testbed and research factories used in the literature. Papers relating to so called learning factories (LF) were reviewed, but only those used in research activities were included. Section 2 reviews previous surveys of testbeds and demonstrators. Section 3 outlines the results of the review conducted of existing manufacturing research demonstrators. Building on this, Section 4 outlines the multi-factory demonstrator created to meet the shortcomings of current systems. Finally, Section 5 outlines the key conclusions and future work.

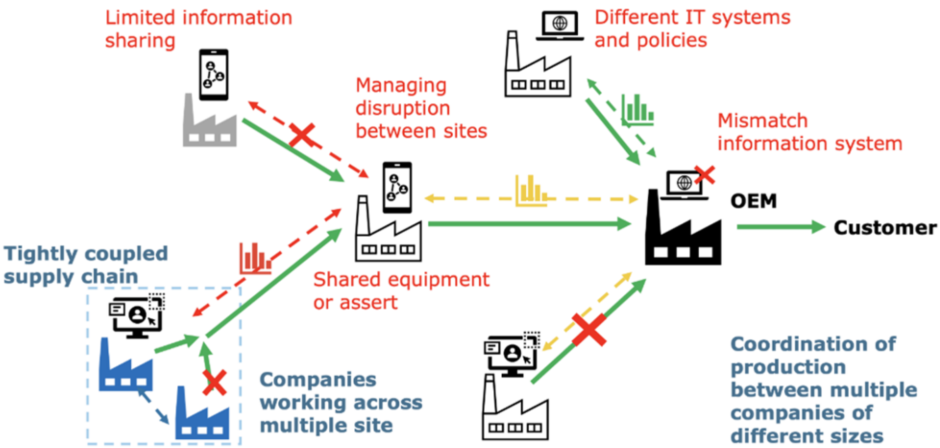

Figure 1. Operational challenges and barriers to inter-connected companies

2. Previous demonstrator and testbed surveys and research

Few studies have focused exclusively on reviewing demonstrators and testbeds in smart manufacturing. Most existing reviews can be found in papers outlining new demonstrators. There have been several surveys of LF, many of which are also utilised for research. Bellucci et al. reviewed nine LF, focusing on products made and processes used [5]; most LF focus on assembling a product with few or no smart features and electronics. Other surveys of LF include Wagner et al., who attempted to highlight factors that enable changeability [6]. Abele et al. review LF and highlights many used in research projects but primarily focus on the LF use for education enhancement [7].

Although all these reviews highlight examples of research demonstrators, there is a lack of detail on the physical sub-systems of the demonstrators and research conducted.

Kim et al. reviewed ten reconfigurable manufacturing testbeds [8]; they noted a focus on scalability and interoperability but less research to automate the reconfiguration operations. Conti, Donadel and Turrin reviewed industrial control system testbeds; however, the majority of testbeds focus on cyber security of key infrastructure such as water, power or transport systems with little focus on manufacturing operations [3]. Salunkhe et al. identified cyber-physical production testbeds, the majority of which focus on electrical grids, cyber security or communication research, with only 8% directly focusing on manufacturing production and operations [4].

As will be discussed in the next section, there are, however, many papers written which refer to testbeds and demonstrators as part of a broader manufacturing systems project. The survey to follow aims to make a systematic review of testbeds, the aims and focus of their development, and how it is used to support underlying research.

3. Survey of smart manufacturing demonstrator environments

3.1. Methodology

This review focused on identifying demonstrators previously presented in published literature. Only systems physically built and combining multiple workstations, robots or machines in a production process were included. Demonstrations constructed over the previous 20 years were chosen because these were more likely to draw on concepts of Industry 4.0, such as IoT, AR, data analysis or artificial intelligence (AI). Demonstrators which consisted of a single robot, machine or process were excluded. Databases such as ScienceDirect, Web of Science and IEEE and Taylor Francis were searched with the key terms *demonstrator, testbed, research factories* and *experiment* in combination with either *factory*, *manufacturing*, *smart factory*, *cyber-physical*, or *industry 4.0*. Research on LF was also searched, though only demonstrators used in research and not just teaching were included. A total of 21 different demonstrators were identified, matching the original criteria. Six demonstrators that met all the criteria were excluded because no published research was found, or they were only simulations. Only a selection of the 118 papers identified is referenced in this review.

3.2. Key demonstrators

Table 1 shows the demonstrators and the home country and organisation identified in the review. Multiple phases or project parts are indicated by decimal numbers (e.g. 1.1 and 1.2). Demonstrators are listed by the year they were first launched or the year of the first research publication if no launch or opening date is published. Table 1 shows a significant concentration of demonstrators in the USA and Europe, possibly due to the prohibitively high cost of setting up a demonstrator, as noted by [6]. More demonstrators were launched in the last ten years (2013-2023) than in the proceeding ten (2003-2013). This could be due to cheaper key components (sensors, robots, and PLCs) or because the search criteria utilised terms such as cyber-physical and industry 4.0, which have become prevalent in the last ten years.

Table 1. Table of key demonstrators and testbeds identified, including details of the organisation, country, references to the research, and the year the demonstrator is first noted in publications.

#	Name	Acronym	Year	Organisation	Country	Ref.
1.1	Cambridge Holonic Packing Cell	CHPC	2003	University of Cambridge	UK	[9]
1.2	Disturbance Tolerant Assembly	DTA	2015	University of Cambridge	UK	[10]
2.1	Distributed reconfigurable factory testbed	DRFT	2004	University of Michigan	USA	[11]
2.2	System-level Manufacturing and Automation Research Testbed	SMART	2017	University of Michigan	USA	[12]
3.1	Soup Factory	SF	2007	SmartFactory^{KL}	Germany	[13]
3.2	Production Level 4	PL4	2020	SmartFactory^{KL}	Germany	[14]
4	Darmstadt process learning factory	DPLF	2007	TU Darmstadt	Germany	[15]
5	AutFab	AF	2012	University of Applied Sciences Darmstadt	Germany	[16]
6	iFactory	IF	2012	University of Windsor	Canada	[17]
7	MTA SZTAKI Learning Factory	MS-LF	2013	Hungarian Academy of Sciences	Hungary	[18]
8	Smart Mini Factory	SMF	2014	University of Bolzano	Italy	[19]
9	Automated Classroom	AC	2015	University of Applied Sciences Emden Leer	Germany	[20]
10	Braunschweig Learning Factory	BLF	2016	TU Braunschweig learning factory	Germany	[21]
11	FASTory Simulator	FAST	2016	Tampere University of Technology	Finland	[22]
12	NIST Smart Manufacturing Systems	SMS	2017	National Institute of Standards and Technology	USA	[23]
13	TU Wien Pilot Factory	W-PF	2017	TU Wien	Austria	[24]
14	Cyber-Physical Production Testbed	CPPT	2018	Chalmers University	Sweden	[4]
15	University of Aalborg Smart Factory	ASM	2019	University of Aalborg	Denmark	[25]
16	SUPSI Mini factory	SUPSI-MF	2019	University of Applied Sciences and Arts Southern Switzerland	Switzerland	[26]
17.1	RICAIP Brno testbed	RICAIP-Brno	2019	Central European Institute of Technology	Czech Republic	[27]
17.2	RICAIP Prague testbed	RICAIP-Prague	2019	University of Prague	Czech Republic	[28]
17.3	RICAIP Saarbrücken testbed	RICAIP-DZ	2019	DFKI and ZeMA	Germany/ Czech Republic	[29]
18	Industrial IoT Testbed	IIOTT	2020	University of Applied Sciences Dresden	Germany	[30]
19	Modular Factory Testbed	MFT	2020	Ulsan National Institute of Science and Technology	South Korea	[8]
20	Open-Digital-Industrial and Networking	ODIN	2021	University of Patras	Greece	[31]
21	Omnifactory	OMNI	2023	University of Nottingham	UK	[32]

3.3. Machines and manufacturing processes

Table 2 shows the key components of the smart factory demonstrators identified. The most common features include automated part dispensers, robotic assembly, and co-robotic assembly stations. CNC milling machines are the most common machining process utilised. Production processes are most often monitored using RFID tracking, visual cameras, and energy use; temperature and vibration monitoring is not utilised as frequently. This could be because they are utilised more frequently in research older than 20 years, and researchers have avoided repeating work already done. AGVs are used in only five demonstrators for transporting parts, with the predominant mode of transport for parts being a conveyor belt.
The ASM [25], IIOT [30] and iFactory [17] demonstrators are based on the same modular components made by Festo. These allow easy reconfiguration, but they limit production to smaller products and set processes.

3.4. Research conducted

Research conducted on the demonstrators often focuses on similar areas. Table 3 shows the most frequently identified research topics. Research on machine-to-machine communications, product tracking, process monitoring, reconfigurable manufacturing and AR/VR training is the most frequently investigated. Less research was identified for DT, factory simulation or AI. However, there has been significant academic research in these areas; work conducted may not have been directly applied to a demonstrator and focused instead on industrial trials, simulations, or individual machine tests. The modular nature of many demonstrators has led to lots of research in distributed control and reconfigurable manufacturing. Internal factory communication research has focused on machine-to-machine communication with protocols such as OPC-UA or MTConnect used. Less research has focused on the vertical connection of shop floor IoT to enterprise-level ERP and MES functions, potentially because many demonstrators are not utilising this software or do not require this level of integration.

Table 2. Summary of the machining processes, assembly methods, transportation, sensors and monitoring and other capabilities or equipment used in each demonstrator.

		Processes					**Assembly**				**Transport**				**Sensors or monitoring**					**Other**			
#	**Name**	**3D printing**	**CNC milling**	**Drilling**	**Laser cutting**	**Other**	**Manual**	**Robotic**	**Co-robotic**	**None**	**Monorail track**	**Conveyor belt**	**AGVs**	**Workers**	**RFID**	**Energy Monitoring**	**Temperature**	**Vibration**	**Visual (camera)**	**AR**	**VR**	**Automated dispensing**	**Modular design**
1.1	CHPC							✓			✓				✓								
1.2	DTA		✓			✓		✓			✓				✓							✓	
2.1	DRFT		✓					✓				✓	✓		✓								
2.2	SMART		✓					✓				✓			✓		✓		✓			✓	
3.1	SF					✓				✓					✓							✓	✓
3.2	PL4							✓			✓				✓				✓	✓		✓	✓

4	DPLF		✓				✓							✓					✓	✓			✓
5	AF					✓		✓			✓				✓	✓			✓				
6	IF		✓				✓	✓				✓				✓						✓	
7	MS-LF			✓		✓		✓	✓		✓											✓	✓
8	SMF						✓	✓	✓				✓	✓	✓						✓		
9	AC	✓			✓				✓			✓				✓						✓	
10	BLF					✓						✓				✓	✓						✓
11	FAST							✓				✓				✓							✓
12	SMS		✓							✓						✓	✓	✓					
13	W-PF		✓				✓		✓					✓	✓					✓		✓	
14	CPPT						✓		✓			✓			✓								✓
15	ASM			✓				✓				✓						✓	✓			✓	✓
16	SUPSI-MF	✓	✓		✓		✓					✓					✓		✓			✓	
17.1	RICAIP -Brno	✓	✓		✓	✓			✓				✓					✓			✓	✓	
17.2	RICAIP -Prague	✓	✓		✓	✓		✓	✓		✓			✓	✓						✓		
17.3	RICAIP – DZ					✓			✓				✓							✓			
18	IIOTT		✓					✓	✓			✓			✓	✓						✓	
19	MFT							✓											✓			✓	✓
20	ODIN			✓				✓	✓										✓				
21	OMNI	✓				✓	✓	✓	✓				✓		✓				✓				
Total		5	11	3	4	9	7	16	11	2	6	10	5	4	13	7	4	3	9	4	3	12	9

3.5. Discussion

Tables 2 and 3 give a good overview of existing demonstrators and show what technology has been utilised and research conducted. As noted in other reviews, robotic or co-robotic assembly is a common process seen in nearly all demonstrators in some form [5]. Unlike Salunkhe et al. [4], few research was identified related to cyber security on these testbeds. Gaps in the existing demonstrators' design and use were identified:

- Research has predominantly focused on single operations or multiple, closely connected operations. There has been little consideration of the connection between factory sites, suppliers, or customer factories. One exception includes PL4 [14], which can receive orders from other factories as part of the EU GAIA-X [27] project. Similarly, the RICAIP [27] demonstrator aims to share design and order information to enable cross-site production.
- Increases or decreases in the volume of orders are not investigated, only the product change. Production tests are also limited to low runs of below five products. This means the full complexity of production and the transfer of resources within a factory is not accounted for.
- Product size is often limed to small, relatively simple products. Gluing or screwing processes add complexity to assemblies, and snap fittings are predominantly used for products. The exception is OMNI which assembles larger-scale aerospace components [32].
- Demonstrators are often built on new equipment or components with built-in sensing or processing capabilities not seen on older equipment. DPLF [15], SMS [23] and SMART [12] use legacy equipment with no sensing capabilities added, but data is often not used beyond the machine level.

Table 3. Summary of research topics investigated using each demonstrator.

#	Research Topic	Reconfigurable manufacturing	Energy monitoring	Process monitoring	Production quality monitoring	Production tracking	Agent or distributed control	MES development or integration	ERP development or integration	Human-robot collaboration	AR or VR training	Machine-to-machine communication	Factory operation simulations	Digital Twins	AI
1.1	CHPC					✓	✓								
1.2	DTA			✓	✓	✓	✓					✓			
2.1	DRFT	✓		✓		✓						✓			
2.2	SMART			✓	✓	✓	✓						✓		✓
3.1	SF			✓		✓	✓					✓			
3.2	PL4					✓		✓			✓				
4	DPLF			✓							✓				
5	AF		✓	✓	✓	✓		✓	✓						✓
6	IF	✓	✓				✓						✓		
7	MS-LF									✓					
8	SMF			✓		✓		✓	✓	✓	✓	✓			
9	AC		✓						✓			✓	✓		
10	BLF		✓	✓											
11	FAST			✓				✓			✓	✓	✓	✓	
12	SMS		✓									✓			
13	W-PF	✓				✓				✓	✓			✓	
14	CPPT	✓				✓	✓			✓		✓			
15	ASM	✓					✓	✓				✓			
16	SUPSI-MF	✓			✓										
17.1	RICAIP - Brno	✓		✓						✓	✓			✓	
17.2	RICAIP - Prague			✓		✓	✓				✓			✓	
17.3	RICAIP – DZ									✓	✓				✓
18	IIOTT		✓			✓						✓			✓
19	MFT	✓					✓	✓			✓				
20	ODIN	✓							✓	✓				✓	
21	OMNI	✓				✓				✓		✓	✓	✓	✓
Total		10	6	11	3	13	9	6	4	8	9	11	5	6	5

4. A Multi-Site Multi-Operation Demonstrator

4.1. Rational

A new multi-site multi-operation demonstrator has been developed to address several gaps identified in the previous section. The design of the so-called Variable Operation and Organisation Management (VOOM) demonstrator is outlined in the section. The demonstrator is one several systems being developed as part of the Made Smarter Connected Factories (MSCF) project [33]. Most previous demonstrators have focused on a single assembly line or production site, many collect extensive process quality and operation data using it to optimise production in that single site or assembly line. However, this data can help with operations not only at that location (factory) but with suppliers and customer factories in the whole value chain. There is an opportunity for manufacturers, suppliers, and customers to operate as *connected factories* with information exchange within and outside the factory. Th demonstrator (based at the University of Cambridge) emulates how multiple SME manufacturers can operate as a *connected factory*. This will enable research into inter-site operation and the associated challenges. Production information will be collected and communicated between production sites.

Many demonstrators are constructed using the latest technology and equipment many companies may not have. The VOOM demonstrator will utilise new technology alongside legacy equipment used in earlier projects (CHPC [9] and DTA [10]). This replicates the situation in many companies where new equipment is often used alongside old, with different data and information available from each machine.

The short production runs often used in previous demonstrators ([17], [21], [27]) make experimentation easier but means issues of long-term reliability and robustness of solutions are often neglected. Unlike previous demonstrator experiments, multiple production runs will be conducted in VOOM with orders of different volumes and product mixes. The initial product is a fixed-speed gearbox with screw fittings, and 3D-printed gears, assembled using robots and workers. Future production will focus on smart sensors and industrial control panels.

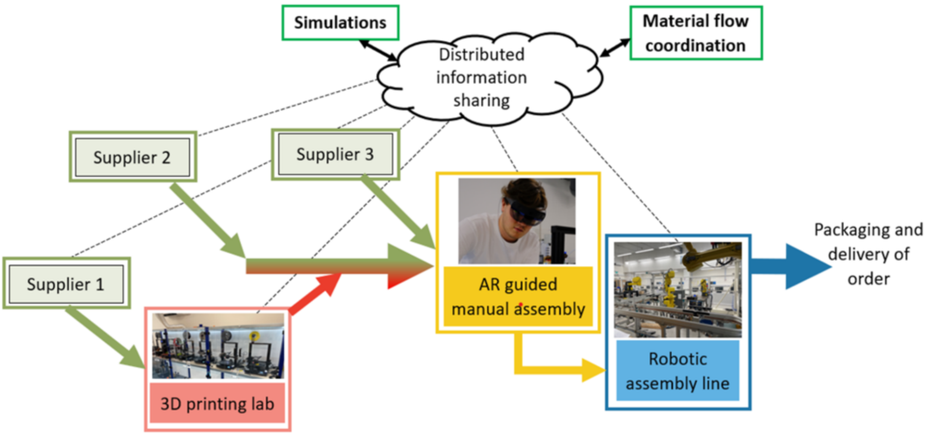

Figure 2. Diagram of the Variable Operations and Organisation Management (VOOM) Demonstrator, showing an example of production flow between the sites.

4.2. Aims of Demonstrator System

The VOOM demonstrator has four main aims: (i) To create a coordinated, adaptable production flow that can change location, volume, mix and production resources. This differs from previous demonstrators that focused on single production lines or sites. Other demonstrators [19], have also focused on SMEs but not considered multiple site interactions. (ii) It will enable adjustable data sharing between companies, facilities, or labs. This would not be possible in a regular factory environment where researchers cannot change information-sharing policies and may only have visibility of information in one site, not throughout the value chain. (iii) it aims to investigate how data sharing and AI can be used within and between production facilities or companies to respond to different scenarios. Scenarios could include the loss of a machine, an unexpected rush order, delays in production or adaptation to a new product. (iv) Multiple mix and volume production experiments will be run; the aim is to capture the cost drivers in production and optimise production to deal with mix and volume changes. (v) The demonstrator will integrate novel low-cost solutions to support distributed production across multiple *connected factories*. This is because costly new technologies are often unaffordable to SMEs who must be included in the connect factory system.

4.3. Development

A diagram of the final demonstrator is shown in Figure 2. Production is coordinated across multiple factory sites, each in a different location (factory) in the Institute for Manufacturing at Cambridge. 3D printing production is used to create a variety of parts with low change over time and worker input; production is supported by machine learning which autonomously corrects errors in production using AI [34]. AR assembly is used before or after robotic assembly to handle complex assemblies unsuitable for robots. AR guides train users to assemble the required components or repair machines [35]. The robotic assembly utilises a monorail to move trays between stations with Fanuc SCARA and LR Mate robots to perform different assembly actions. Low-cost digital solutions developed as part of the Digital Manufacturing on a Shoestring [36] project are integrated into all the factory sites to support production and enable the collection of data from legacy equipment. Suppliers are replicated with different warehouse facilities on different sites.

4.4. Future experimental plan

Future research on the demonstrator is being conducted in four different phases. The phases were planned in collaboration with other university partners and based on the demonstrator's and labs' existing capabilities. Later phases build on the work in the earlier project phases.

Phase 1 will focus on manufacturing gearboxes with different gear ratios, materials, and volumes. Sensors will collect data on production, especially factors impacting production cost and time.

Phase 2 involves the integration of MES functions to help manage the production process. Data on production progress and orders will be shared between sites to enable multi-site production coordination. Challenges, such as a missing worker or broken machines, will be replicated in experiments.

Phase 3 will see new products produced alongside the initial gearbox. Data sharing will be expanded to include information from other sources, such as machine availability and production quality. Concepts such as federated learning, distributed control, and data sharing will be tested.

Phase 4 will expand the demonstrator to more sites integrating production demonstrators from other Made Smarter Connected Factories Centre universities, such as Omnifactory [32] at the University of Nottingham and the University of Sheffield.

5. Summary

This paper reviews 21 different demonstrators previously used in smart factory research. The review identified that existing demonstrators are predominantly restricted to a single production line in a single factory site, and often only a single production run was shown in the results. A newly developed demonstrator simulating production across multiple sites is outlined. The demonstrator aims to enable advanced manufacturing research in new areas not previously validated on a physical demonstrator, including inter-factory coordination and data sharing between sites. Future research is outlined, with the final demonstrator aiming to be integrated with other institution demonstrators. The researchers also aim to investigate architectures, frameworks and standards that could support multiple site production and the integration of multiple low-cost digital solutions.

References

[1] Make UK, 'No Weak Links: Building Supply Chain Resilience', 2023.
[2] H. Şahin and B. Topal, 'Examination of effect of information sharing on businesses performance in the supply chain process', *Int. J. Prod. Res.*, vol. 57, no. 3, pp. 815–828, Feb. 2019, doi: 10.1080/00207543.2018.1484954.
[3] M. Conti, D. Donadel, and F. Turrin, 'A Survey on Industrial Control System Testbeds and Datasets for Security Research', *IEEE Commun. Surv. Tutor.*, vol. 23, no. 4, pp. 2248–2294, 2021, doi: 10.1109/COMST.2021.3094360.
[4] O. Salunkhe, M. Gopalakrishnan, A. Skoogh, and Å. Fasth-Berglund, 'Cyber-Physical Production Testbed: Literature Review and Concept Development', *Procedia Manuf.*, vol. 25, pp. 2–9, Jan. 2018, doi: 10.1016/j.promfg.2018.06.050.
[5] M. Bellucci, A. Chiurco, A. Cimino, D. Ferro, F. Longo, and A. Padovano, 'Learning Factories: a review of state of the art and development of a morphological model for an Industrial Engineering Education 4.0', in *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, Jun. 2022, pp. 260–265. doi: 10.1109/MELECON53508.2022.9843084.
[6] U. Wagner, T. AlGeddawy, H. ElMaraghy, and E. MŸller, 'The State-of-the-Art and Prospects of Learning Factories', *Procedia CIRP*, vol. 3, pp. 109–114, Jan. 2012, doi: 10.1016/j.procir.2012.07.020.
[7] E. Abele *et al.*, 'Learning factories for future oriented research and education in manufacturing', *CIRP Ann.*, vol. 66, no. 2, pp. 803–826, Jan. 2017, doi: 10.1016/j.cirp.2017.05.005.
[8] D.-Y. Kim *et al.*, 'A modular factory testbed for the rapid reconfiguration of manufacturing systems', *J. Intell. Manuf.*, vol. 31, no. 3, pp. 661–680, Mar. 2020, doi: 10.1007/s10845-019-01471-2.
[9] M. Fletcher, D. Mcfarlane, A. Lucas, J. Brusey, and D. Jarvis, *The Cambridge Packing Cell — A Holonic Enterprise Demonstrator*, vol. 2691. 2003, p. 543. doi: 10.1007/3-540-45023-8_51.
[10] J. Um, R. Srinivasan, A. Thorne, and D. McFarlane, 'Smart tracking to enable disturbance tolerant manufacturing through enhanced product intelligence', in *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, Jul. 2015, pp. 1354–1360. doi: 10.1109/INDIN.2015.7281932.
[11] J. Luntz, E. E. Almeida, D. Tilbury, J. Moyne, and K. Hargrove, 'The Distributed Reconfigurable Factory Testbed (Drft): A Collaborative Cross University Manufacturing System Testbed.', in *2006 Annual Conference & Exposition Proceedings*, Chicago, Illinois: ASEE Conferences, Jun. 2006, p. 11.1274.1-11.1274.21. doi: 10.18260/1-2--1403.
[12] I. Kovalenko, M. Saez, K. Barton, and D. Tilbury, 'SMART: A System-level Manufacturing and Automation Research Testbed', *Smart Sustain. Manuf. Syst.*, vol. 1, no. 1, p. 20170006, Oct. 2017, doi: 10.1520/SSMS20170006.
[13] D. Zuehlke, 'SmartFactory – A Vision becomes Reality', *IFAC Proc. Vol.*, vol. 42, no. 4, pp. 31–39, Jan. 2009, doi: 10.3182/20090603-3-RU-2001.0578.
[14] M. Birtel, F. Mohr, J. Hermann, P. Bertram, and M. Ruskowski, 'Requirements for a Human-Centered Condition Monitoring in Modular Production Environments', *IFAC-Pap.*, vol. 51, no. 11, pp. 909–914, Jan. 2018, doi: 10.1016/j.ifacol.2018.08.464.
[15] E. Abele and J. Metternich, 'TU Darmstadt - Process Learning Factory'.
[16] S. Simons, P. Abé, and S. Neser, 'Learning in the AutFab – The Fully Automated Industrie 4.0 Learning Factory of the University of Applied Sciences Darmstadt', *Procedia Manuf.*, vol. 9, pp. 81–88, 2017, doi: 10.1016/j.promfg.2017.04.023.

[17] T. AlGeddawy and H. ElMaraghy, ‘Design for energy sustainability in manufacturing systems’, *CIRP Ann.*, vol. 65, no. 1, pp. 409–412, Jan. 2016, doi: 10.1016/j.cirp.2016.04.023.

[18] Z. Kemény, R. Beregi, B. Tipary, K. Abai, and J. Nacsa, ‘Recent advances in learning content and infrastructure development for layout and process planning courses at the SZTAKI learning factories’, *Procedia Manuf.*, vol. 45, pp. 319–324, Jan. 2020, doi: 10.1016/j.promfg.2020.04.024.

[19] L. Gualtieri *et al.*, ‘Advanced Automation for SMEs in the I4.0 Revolution: Engineering Education and Employees Training in the Smart Mini Factory Laboratory’, in *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Dec. 2018, pp. 1111–1115. doi: 10.1109/IEEM.2018.8607719.

[20] J. Wermann, A. W. Colombo, A. Pechmann, and M. Zarte, ‘Using an interdisciplinary demonstration platform for teaching Industry 4.0’, *Procedia Manuf.*, vol. 31, pp. 302–308, 2019, doi: 10.1016/j.promfg.2019.03.048.

[21] K. S. Sangwan *et al.*, ‘Comparative Analysis for Solar Energy Based Learning Factory: Case Study for TU Braunschweig and BITS Pilani’, *Procedia CIRP*, vol. 69, pp. 407–411, Jan. 2018, doi: 10.1016/j.procir.2017.11.018.

[22] W. M. Mohammed and J. L. Martinez Lastra, ‘FASTory digital twin data’, *Data Brief*, vol. 35, p. 106912, Feb. 2021, doi: 10.1016/j.dib.2021.106912.

[23] A. Barnard Feeney, S. Frechette, and V. Srinivasan, ‘Cyber-Physical Systems Engineering for Manufacturing’, 2017, pp. 81–110. doi: 10.1007/978-3-319-42559-7_4.

[24] G. Reisinger, T. Komenda, P. Hold, and W. Sihn, ‘A Concept towards Automated Data-Driven Reconfiguration of Digital Assistance Systems’, *Procedia Manuf.*, vol. 23, pp. 99–104, Jan. 2018, doi: 10.1016/j.promfg.2018.03.168.

[25] S. Mantravadi, C. Møller, C. LI, and R. Schnyder, ‘Design choices for next-generation IIoT-connected MES/MOM: An empirical study on smart factories’, *Robot. Comput.-Integr. Manuf.*, vol. 73, Feb. 2022, doi: 10.1016/j.rcim.2021.102225.

[26] F. Daniele, M. Confalonieri, P. Pedrazzoli, A. Graf, A. Ferrario, and M. Foletti, ‘Implementation of a learning factory for research, education and training: the SUPSI Mini-Factory’, *SSRN Electron. J.*, Jan. 2021, doi: 10.2139/ssrn.3858404.

[27] L. Zalud, F. Burian, and P. Kalvodova, ‘Industry 4.0 Testbed at Brno University of Technology’, in *Modelling and Simulation for Autonomous Systems*, J. Mazal, Ed., in Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 147–157. doi: 10.1007/978-3-030-14984-0_13.

[28] D. Winkler, P. Novák, J. Vyskočil, K. Meixner, and S. Biffl, ‘Industry 4.0 Asset-based Risk Mitigation for Production Operation’, in *2021 IEEE 17th International Conference on Automation Science and Engineering (CASE)*, Aug. 2021, pp. 278–285. doi: 10.1109/CASE49439.2021.9551419.

[29] Unkown, ‘Research and Innovation Centre on Advanced Industrial Production’, *RICAIP*. https://ricaip.eu/ (accessed Dec. 01, 2022).

[30] ‘Making Digitalisation Tangible at The Industrial IoT Testbed’. https://www.htw-dresden.de/en/hochschule/fakultaeten/info-math/forschung/smart-production-systems/translate-to-english-industrie-40-modellfabrik (accessed Jan. 30, 2023).

[31] S. Makris *et al.*, ‘Open-Digital-Industrial and Networking pilot lines using modular components for scalable production – ODIN project approach’, *Procedia CIRP*, vol. 106, pp. 162–167, 2022, doi: 10.1016/j.procir.2022.02.172.

[32] F. Mo *et al.*, ‘A framework for manufacturing system reconfiguration and optimisation utilising digital twins and modular artificial intelligence’, *Robot. Comput.-Integr. Manuf.*, vol. 82, p. 102524, Aug. 2023, doi: 10.1016/j.rcim.2022.102524.

[33] ‘Research Center For Connected Factories’. https://www.madesmarter.uk/made-smarter-innovation/research-centres/research-centre-for-connected-factories/ (accessed May 19, 2023).

[34] D. A. J. Brion and S. W. Pattinson, ‘Generalisable 3D printing error detection and correction via multi-head neural networks’, *Nat. Commun.*, vol. 13, no. 1, Dec. 2022, doi: 10.1038/s41467-022-31985-y.

[35] L. Solari Bozz, K. Samson, S. Tadeja, S. Pattinson, and T. Bohne, ‘Towards Augmented Reality Guiding Systems: An Engineering Design of an Immersive System for Complex 3D Printing Repair Process’, presented at the IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)., 2023. Accessed: Apr. 17, 2023. [Online]. Available: https://doi.org/10.17863/CAM.93609

[36] G. Hawkridge, D. McFarlane, J. Kaiser, L. de Silva, and G. Terrazas, ‘Designing Shoestring Solutions: An Approach for Designing Low-Cost Digital Solutions for Manufacturing’, in *Service Oriented, Holonic and Multi-agent Manufacturing Systems*, T. Borangiu, D. Trentesaux, P. Leitão, O. Cardin, and L. Joblot, Eds., in Studies in Computational Intelligence, vol. 1034. Cham: Springer International Publishing, 2022, pp. 249–262. doi: 10.1007/978-3-030-99108-1_18.