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Industry 4.0 and the Imperative of Professional Retraining: Non-Formal Digital Learning for the Manufacturing Workforce

Dan Cătălin Bîrsan[1]*
[1]Department of Manufacturing Engineering, "Dunărea de Jos" University of Galați, Romania
*Corresponding author: dbirsan@ugal.ro

Abstract. The transition to Industry 4.0 is reshaping manufacturing work faster than formal education systems can respond, creating an urgent need to retrain the existing workforce. This paper examines the role of non-formal digital learning in reskilling and upskilling manufacturing employees for technologically advanced production environments. The study is a narrative and critical review of peer-reviewed literature, foundational scholarship and industry reports published mainly between 2015 and 2024, identified through academic databases and synthesised thematically around skill requirements, learning modalities and implementation conditions. The reviewed evidence indicates that the manufacturing skill profile is shifting towards digital, data-related and transversal competences, and that non-formal and workplace learning, delivered through e-learning, micro-credentials, virtual and augmented reality simulation and adaptive platforms, is well suited to providing this retraining flexibly and at scale. Persistent barriers include unequal digital access, the cost and time burden on employers and learners, weak recognition of non-formally acquired skills, and a tendency to prioritise technology over the worker. Non-formal digital learning is a necessary, though not sufficient, instrument for workforce retraining in Industry 4.0. Its effectiveness depends on a culture of lifelong learning, robust mechanisms for validating informal achievement, and collaboration among industry, education providers and policymakers, applied through human-centred rather than purely technology-driven strategies.

Keywords: Industry 4.0; Reskilling; Non-formal learning; Digital learning; Manufacturing workforce.

1. Introduction

The fourth industrial revolution, commonly termed Industry 4.0, denotes the integration of cyber-physical systems, the industrial internet of things, big-data analytics, advanced robotics and artificial intelligence into manufacturing (Liao et al., 2017). These technologies are reorganising the factory floor, automating routine operations and shifting human work towards the supervision, configuration and maintenance of intelligent systems. In doing so, they change not only how goods are produced but also the competences that production workers are expected to hold (Hecklau et al., 2016).

This technological shift has opened a pronounced skills gap. Industry surveys report that a large share of the workforce will require retraining within a few years, as established competences become obsolete and new digital ones rise in importance (World Economic Forum, 2023). The pressure is intensified by demographic change, since an ageing manufacturing workforce and

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limited inflows of younger, digitally fluent workers leave many established employees in need of substantial reskilling (Maisiri et al., 2019; Li, 2024).

Formal education and initial vocational training, although essential, adapt comparatively slowly and reach mainly those entering the labour market rather than those already in it. Retraining the incumbent workforce at the required pace therefore depends heavily on non-formal and workplace learning, which is flexible, modular and able to deliver targeted competences at the moment of need (Eraut, 2000; Tynjälä, 2008). The increasing availability of digital tools has expanded the reach of such provision, yet much of the Industry 4.0 literature concentrates on identifying which skills are needed rather than on how non-formal digital learning can deliver them.

Against this background, the paper has three objectives: to characterise the shift in skill requirements brought about by Industry 4.0 in manufacturing; to examine the non-formal digital learning modalities available for reskilling the workforce; and to discuss the organisational and policy conditions that enable or constrain their use. The significance of the topic lies in the fact that the success of Industry 4.0 depends as much on workforce capability as on the technologies themselves.

2. Research methodology

The paper adopts a narrative and critical review rather than a formal meta-analysis. This approach was chosen because the evidence is dispersed across engineering, management and education literatures and across publication types, and because the aim is to synthesise concepts and identify patterns rather than to aggregate comparable experimental results.

Relevant sources were identified through searches of major academic databases, including Scopus, Web of Science and Google Scholar, using combinations of terms such as “Industry 4.0”, “reskilling”, “upskilling”, “workplace learning”, “non-formal learning” and “manufacturing workforce”. Priority was given to peer-reviewed articles and recognised reviews published mainly between 2015 and 2024, supplemented by foundational works on workplace learning and by an authoritative industry report (World Economic Forum, 2023).

Selected works were read and grouped thematically according to the skill requirements they described, the learning modalities they addressed and the implementation conditions they identified. This interpretive synthesis supports the drawing of cross-cutting conclusions, but it does not claim the exhaustiveness or replicability of a review conducted under a strict systematic protocol, a limitation acknowledged in the conclusion.

3. Results

The reviewed literature can be organised around four themes: the changing skill profile of the manufacturing workforce; non-formal and workplace learning as a delivery mechanism; the digital modalities through which retraining is provided, summarised in Table 1; and the organisational and policy conditions that shape outcomes.

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3.1 The changing skill profile of the manufacturing workforce

Studies of Industry 4.0 competences consistently distinguish two broad categories. The first is a set of technical and digital skills, including data literacy, familiarity with the internet of things and automation, basic programming, and the operation of cyber-physical and robotic systems (Maisiri et al., 2019; Hecklau et al., 2016). The second is a set of transversal or non-technical skills, such as problem-solving, adaptability, collaboration and, above all, the disposition and capacity for continuous learning (World Economic Forum, 2023). The recurring conclusion is that the most durable competence is the ability to keep learning, because specific technical skills date quickly.

3.2 Non-formal and workplace learning as a delivery mechanism

Non-formal learning refers to organised, intentional learning that takes place outside the formal qualification system, while related informal learning arises through everyday work activity (Eraut, 2000). Research on workplace learning shows that much professional competence is acquired through practice, problem-solving and interaction on the job rather than through classroom instruction alone (Tynjälä, 2008). These characteristics make non-formal and workplace learning particularly suited to Industry 4.0 retraining, which must be timely, role-specific and compatible with continued production.

3.3 Digital modalities for reskilling

A range of digital modalities now supports non-formal retraining. Online courses and learning-management systems deliver scalable, self-paced instruction, while short courses and micro-credentials allow targeted competences to be acquired and certified without lengthy programmes (World Economic Forum, 2023). Virtual and augmented reality enable immersive, hands-on practice of assembly, maintenance and safety procedures in a safe and repeatable environment, reducing risk and the need for live equipment (Gavish et al., 2015). Adaptive and data-driven platforms further personalise content and pace to the individual learner. Such tools are increasingly embedded in manufacturers' training strategies and in the qualification of personnel for digitalised production (Benesóvá & Tupa, 2017; Sima et al., 2020).

3.4 Organisational and policy conditions

The evidence is clear that technology alone does not secure successful retraining. Employer investment, supportive work organisation and a culture that values continuous development are decisive, and returns on training investment are widely reported by employers (World Economic Forum, 2023; Li, 2024). At a systemic level, collaboration among industry, education providers and government is repeatedly identified as essential to align provision with evolving skill needs and to share the cost and risk of large-scale reskilling (Maisiri et al., 2019; Sima et al., 2020).

Table 1. Non-formal digital learning modalities for reskilling the manufacturing workforce.

Modality	**Examples**	**Strengths**	**Limitations**
E-learning and LMS	Online courses; corporate learning platforms	Scalable, self-paced, low marginal cost	Variable engagement; needs self-direction

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Micro-credentials	Short certified courses; digital badges	Targeted, fast, stackable competences	Uneven recognition across employers
VR and AR simulation	Immersive assembly, maintenance and safety training	Safe, repeatable, hands-on practice	High setup cost; hardware requirements
Adaptive and AI platforms	Personalised content and pacing	Efficient, individualised, real-time feedback	Data and infrastructure demands; opacity

Taken together, these findings show a consistent set of benefits: non-formal digital learning can deliver targeted competences quickly, flexibly and at scale, can be integrated with ongoing work, and can reduce the cost and risk of training through simulation and personalisation (Gavish et al., 2015; World Economic Forum, 2023). At the same time the literature is candid about the barriers. Unequal access to devices, connectivity and digital skills can exclude precisely those workers most in need of retraining; the time and cost of training press on both employers and employees; the competences gained through non-formal routes are often poorly recognised across the labour market; and a persistent technology-centred focus can sideline the needs and motivation of the worker (Maisiri et al., 2019; Sima et al., 2020).

4. Discussion

The findings suggest that retraining for Industry 4.0 is best understood not as a one-off event but as a continuous process embedded in working life. Because specific technical skills date rapidly, the strategic goal is less the transfer of any single competence than the cultivation of an enduring capacity and willingness to learn (Li, 2024; Tynjälä, 2008). Non-formal digital learning is well matched to this goal, since it can supply small, current and role-relevant units of learning repeatedly over a career rather than in a single front-loaded programme.

A central obstacle, however, is the recognition of what is learned outside formal qualifications. Much valuable competence is acquired informally at work, yet it remains invisible to employers and labour markets unless it is made explicit and certified (Eraut, 2000). Micro-credentials and digital badges offer a partial solution by rendering non-formal achievement portable and verifiable, but their value depends on shared standards and on employer trust, which are still uneven (World Economic Forum, 2023). Strengthening the validation of non-formal learning is therefore as important as expanding the provision itself.

The reviewed evidence also cautions against a purely technological reading of the problem. Where reskilling is framed only as the deployment of new tools, the social dimension of work, including worker motivation, the position of older employees and unequal digital access, tends to be neglected (Maisiri et al., 2019; Sima et al., 2020). A human-centred approach, which treats workers as active participants in their own development rather than as recipients of technology,

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is more likely to produce durable capability and to retain experienced staff whose tacit knowledge is difficult to replace.

Finally, the implications extend beyond the individual firm. Effective reskilling at scale appears to require collaboration among industry, education providers and government, both to align provision with fast-changing needs and to share its cost (Hecklau et al., 2016; Benesóvá & Tupa, 2017). Small and medium-sized manufacturers, which form the backbone of the sector yet often lack dedicated training resources, are particularly dependent on such shared infrastructure and on accessible, low-cost digital provision.

5. Conclusion

Industry 4.0 has made the continuous retraining of the manufacturing workforce an imperative rather than an option, and non-formal digital learning has emerged as a primary means of meeting it. Delivered through e-learning, micro-credentials, immersive simulation and adaptive platforms, such learning can provide timely, flexible and scalable reskilling that formal systems alone cannot. The central argument of this paper is that its value is conditional: it depends on a culture of lifelong learning, on credible recognition of non-formally acquired competences, on equitable digital access, and on a human-centred rather than technology-driven approach.

Several limitations should be noted. As a narrative and critical review, the study is interpretive and does not claim the exhaustiveness of a systematic protocol; it relies on English-language sources; and, in a fast-moving field, particular tools and figures date quickly even where the underlying issues persist.

Future research should prioritise empirical and longitudinal evaluation of non-formal digital learning in authentic manufacturing settings, with attention to its effectiveness for different groups of workers, including older and lower-skilled employees. The specific situation of small and medium-sized enterprises, and the design of recognition frameworks that make non-formal learning portable, warrant particular study. The task for firms, educators and policymakers is to treat workforce retraining as a shared, continuous responsibility, so that the human capability on which Industry 4.0 depends keeps pace with the technology itself.

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