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DEVELOPING An OHS SOCIO-TECHNICAL SIMULATION ENVIRONMENT FOR MANUFACTURING WORKFORCE EDUCATION

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The manufacturing sector is a cornerstone of the European economy, relying on a workforce capable of managing complex socio-technical systems (STSs). However, bridging the gap between theoretical knowledge and practical application remains challenging, particularly in large-scale, flexible learning contexts. Conventional teaching methods often lack dynamic complexity and struggle to integrate active learning in time and location independent settings. This paper presents the initial development steps of a novel online simulation environment designed to address these challenges. The solution combines technical system modelling with generative AI-based social simulation to create a holistic, scalable learning tool. The focus is on key competence areas such as Lean Production, Safety, Quality Management, and Human Factors. Generative AI enables realistic representation of human interactions within STSs, complementing simulations of technical processes to provide an integrated learning experience. To ensure rigor, the simulation requirements are derived from stakeholder needs, scientific literature, and regulatory frameworks. International survey data and expert input inform the identification and consolidation of socio-technical factors, which are validated by a multidisciplinary team of experts. These requirements form the foundation for the Erasmus+ project 4SiM (Scalable Socio Technical System Simulation in Manufacturing), which aims to deliver an innovative educational platform by 2028. The paper discusses preliminary findings from the requirements engineering phase and their implications for simulation design. By integrating generative AI with technical system modelling, 4SiM seeks to advance workforce education and enhance resilience in manufacturing systems.

Keywords: Education, Simulation, Socio-technical systems, Safety, Manufacturing

1. Introduction

The European manufacturing landscape is undergoing the so-called "twin transition" which is defined by both digital transformation and sustainability goals (Hofmann Trevisan et al. 2024). First, the focus was on Industry 4.0; the technical integration of digital systems, artificial intelligence (AI), and robotics to achieve efficiency, with less attention on the human element (Marcon et al. 2022). Consequently, attention has shifted towards Industry 5.0 (Passalacqua et al. 2025), highlighting manufacturing systems as complex socio-technical systems where social, organizational, and technological subsystems are jointly aggregated (Marcon et al. 2022; Soliman et al. 2018). Success in this modern manufacturing environment depends on a multi-skilled workforce capable of addressing organizational core tasks, which define the purpose of work and involve managing uncertainties inherent in complex processes (Reiman and Oedewald 2007; Adriaensen et al. 2022). In such complex environments, mitigating interdisciplinary challenges increasingly depends on a multi-skilled workforce (Hofmann Trevisan et al. 2024), but a skill gap regarding the adoption of new and complex technologies has been recognized (Marcon et al. 2022).

One of the root causes for these issues is that existing educational systems often struggle to keep pace with rapid technological acceleration (Hofmann Trevisan et al. 2024) and to capture complexities inherent in socio-technical interactions (Abreu Saurin and Patriarca 2020) and current manufacturing systems (Soliman et al. 2018). Existing simulation environments are observed to be too simplistic, as they ignore details such as human error patterns and social resistance, focusing instead on idealistic design of “work-as-imagined” (Abreu Saurin and Patriarca 2020; Passalacqua et al. 2025). Furthermore, current training infrastructure lacks guidelines to minimize psychosocial risks of modern factories such as technostress, variations in trust, and loss of autonomy (Passalacqua et al. 2025).

Traditional training approaches also tend to neglect Lean and safety practices, despite their critical importance in real-world, dynamic and highly complex production environments (Soliman et al. 2018; Marcon et al. 2022). This gap is aggravated by the “magic human” design fallacy, which assumes that technical automation can rely on human intervention to be prompt and flawless during rare and complex system failures, despite the absence of adequate training for such situations (Adriaensen et al. 2022). Furthermore, manufacturing education tends to be machine-centric, disregarding the modelling of social and technical dimensions of work systems together. These dimensions constitute socio-technical factors (STFs), which are critical for effective education in OHS, lean, and quality domains (Passalacqua et al. 2025; Weiss et al. 2021).

In this study, we examine the design of an active learning approach utilizing Generative AI (GenAI) to address the challenges underlined above. GenAI could enrich a simulation environment with virtual characters that can mimic human variability and social dynamics (Sætra 2021). Such a simulation environment would enable the education of e.g. OHS professionals by using active learning in a way that is scalable and can be utilized even in time and location independent settings. An example of a scenario could be a simulated manufacturing environment with unsafe conditions where the learner can interact with both the technical parts of the system as well as simulated personnel. However, to simulate these scenarios in a rigorous manner, a systematic transformation of stakeholder data into simulation requirements is needed.

An initial stage of this design process is requirements engineering. The aim of this stage is to recognize the socio-technical factors necessary for the development of a high fidelity online simulation platform for manufacturing education, with particular emphasis on Lean, safety, ergonomics and quality domains. More particularly, we focus on expert interviews through which we aim to identify initial requirements for a socio-technical simulation platform, and on their implications for the design of the simulation environment.

These interviews are a part of the ERASMUS+ funded international collaboration project 4SiM (Scalable Simulation of Socio-technical Systems in Manufacturing). The latter stages of the design work, such as validating the initial requirements through surveys and expert workshops, the actual design and implementation work, and validation of the 4SiM platform are beyond the scope of this research and are intended to be addressed in subsequent phases of the study.

2. Literature review

2.1. *Socio-technical systems in manufacturing*

The sociotechnical theory labels manufacturing as complex network of people, tools and organizational structures, a framework that promotes fidelity between performance and workers wellbeing (Reiman and Oedewald 2007).The shift from Industry 4.0 to Industry 5.0 reinforces manufacturing systems as socio-technical systems where social, organizational, and technological subsystems are jointly aggregated (Marcon et al. 2022; Soliman et al. 2018). Manufacturing operations are increasingly shaped by joint cognitive systems, in which cognitive agencies are distributed across humans and intelligent machines. In such systems, decision-making emerges from the interaction between human operators and non-human agents, such as collaborative robots (cobots) (Weiss et al. 2021).

2.2. *Active learning, simulation and GenAI in manufacturing education*

Generative AI is new technological tool that posses transformative capabilities required to address this gap, by putting forward virtual characters that can mimic human variability and social dynamics (Passalacqua et al. 2025; Sætra 2021). However, such an endeavor requires an extensive systematic transformation of stakeholder data into simulation parameters which will eventually help to integrate human-centric components into a scalable digital simulator (Reiman and Oedewald 2007; Abreu Saurin and Patriarca 2020)

Also with emerging Industry 5.0, along with GenAI, active learning is proving to be phenomenal in education as it equips the trainees to avoid errors by making them actively participate in problem solving (Bednar and Welch 2020), consequently increasing retention which makes it effective for lean principles. In addition to that active learning combined with simulation-based learning engages with realism which replicates Joint cognitive system (JCS), ultimately promoting resilience skills and continuous improvement (Adriaensen et al. 2022; Hofmann Trevisan et al., 2024). It has also been observed that in active learning, simulations provide a perfect staging area for trainees to practice failure handling, a safe rehearsal for hazardous tasks.

Another suite of technological tools in this transformative age of twin transition and Industry 5.0, is digital learning (Hofmann Trevisan et al., 2024). It includes virtual learning environments (VLEs) supported through Virtual Reality (VR) Augmented Reality (AR) and various e-learning platforms (Liboni et al. 2019), enabling flexible and personalized training. Another notable platform promoting digital literacy is serious games which rely on gamification to provide training to workers for complex tasks (Brauner and Ziefle 2022). Another mention can be made here by discussing learning factories, which are facilities designed for work-integrated qualification providing hands-on educational experience (Liboni et al. 2019).

3. Methodology

3.1. *Research design*

This study adopts a qualitative, exploratory research design to facilitate the systematic elicitation of requirements for socio-technical educational platforms (Baxter and Sommerville 2011). The exploratory approach is particularly suited to the nature of this research, as it enables an in-depth examination of the current state, prevailing limitations, and unmet needs within manufacturing industry education and training. More specifically, this design allows for the identification of critical pain points experienced by industry stakeholders while capturing the interdependencies between social and technical subsystems.

The data collection phase uses semi-structured interviews to capture the subjective outlook of domain experts. The interview was structured around four themes (i) current and emerging challenges in safety, quality, lean management, ergonomics and human–machine interaction; (ii) limitations of current training approaches; (iii) future skill requirements for operators, engineers, and supervisors; and (iv) perceived feasibility and value of active learning approaches (e.g., simulation-based learning, microlearning, and AI-assisted adaptive learning).

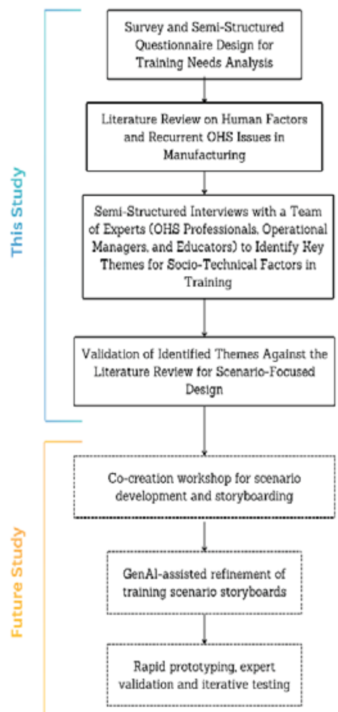

Fig. 1. Research and development process.

3.2. *Participant selection and data collection*

The sample used in this study comprises seven international experts. To cover a diversity of viewpoints, experts from different manufacturing areas and from academia were invited. The sample and the interviews are described in more detail in Table 1. The participant group comprises two academic researchers and five industry practitioners, collectively spanning the domains of lean production, safety management, and ergonomics.

Table 1. Interviews participant group.

ID	Country	Role	Domain
I1	Finland	Product Manager, Ergonomist	Workstation furniture manufacturing
I2	Finland	Factory Head	Industrial labelling manufacturing
I3	Finland	Quality & Compliance Manager	Battery manufacturing
I4	Finland	Lecturer, European Ergonomist	Academia (Ergonomist)
I5	Greece	Chemical Engineer, PhD	OSH Institute
I6	Serbia	Full Professor	Safety, Ergonomics, HRI
I7	Finland	OSH Manager (PhD Candidate)	Vehicle manufacturing

The duration of interviews conducted was approximately 45-60 minutes arranged on online meeting platforms. Consent forms were collected from all the participants prior to the interview. The data collected was anonymized for analysis purposes. Table 2 contains some sample questions of the interviews.

Table 2 Interview overview.

Section of Interview	Sample Questions
Basic Information	*"How does your organization currently approach safety/quality/lean/ergonomics training?"*(Industry Professionals) *"Do you collaborate with industry, specifically in the manufacturing sector?"*(Educators)
Present Challenges	*"What are the biggest health, safety or quality challenges your organization/the industry currently faces?"* *"What prevents staff from consistently applying safe practices in real work conditions?"*
Emerging and Future Challenges	*"What upcoming technologies or processes do you think will change the required safety/quality/lean/ergonomics skills?"*
Current Training Limitations	*"What are the limitations of current training programs/teaching methodologies?"*
Prioritize Training Needs	*"If you had to choose the top 3 emerging health/safety/quality/lean/ergonomics issues that require new training/teaching paradigms, what would they be?"* *"What are the top 3 skills in your organization/sector that should be prioritized in training/teaching?"*
Active Learning and Simulation-Based Training	*"Which active learning approaches do you think could solve your current training (teaching) challenges/would be most valuable in your organization (for your students)?"* *"What barriers exist to adopting new training/teaching approaches?"*

3.3. *Data analysis*

Using (Braun and Clarke 2012) reflexive thematic analysis, the interview data were translated into four themes (Table 3). Collectively, they represent the requirements and needs that should be considered when developing simulation scenarios for manufacturing industry training. Each theme is discussed in the Results section in relation to the research aims, and their implications towards the development can be found in the discussion section.

4. Results

This section summarizes the results of the thematic analysis of the interview data. The identified themes are summarized in Table 3 and elaborated in following subsections.

Table 3. Identified themes.

Theme	Description	Prevalence
1	Ergonomics, human factors and the changing workforce	7/7
2	Safety culture and perceived lean-safety-quality tensions	7/7
3	Human–technology interaction	7/7
4	Issues with current training	7/7

4.1. *Ergonomics, human factors and the changing workforce*

Themes 1 and 2 jointly highlight a human factors deficit, an ageing workforce facing physical, cognitive, and psychosocial demands while operating systems designed with insufficient human factors consideration. All seven participants raised these concerns, noting that manufacturing systems such as machines are developed primarily to maximize production with less attention given to the human element. With average workforce ages approaching 40 years and pension ages also rising, cumulative musculoskeletal stress and declining recovery capacity create operational risks. As I2 noted: *"The average age in both our factories is 40 years plus, so I think that is a challenge for us, that aging workforce."* At the same time, I7 identified mental health and muscles skeletal stress as a growing concern among workers:

"I think the biggest health issue is mental health issues, especially in younger workers. They are rising mental health challenges and the greater use of technology plays (a role in it)" and the second biggest challenge is *"muscles and skeletal diseases"*.

This bidirectional pressure is compounded by limited ergonomic awareness, which can be traced to gaps in education and training on this subject. I1 stated: "*Engineers in Finland are not trained on ergonomics or human factors...... there is basic level understanding of ergonomics in industrial (context)"*. I2 reported that some machines require operators to stand for extended periods with limited opportunity to sit, while frequent movement between tasks leaves little time for rest, particularly when operating large machines that require setup and monitoring. I1 also observed that some workers resist using safety equipment in order to work faster and may downplay the importance of safety protocols, occasionally also ignoring them altogether: *"They think that it takes too much time, so they (would) rather carry (the products) manually instead of using (the) lifter. (That is) really short thinking about (the safety protocols). Similarly* I2 stated that *"It is always possible to hurt yourself in many cases, but mostly it requires negligence of (safety practices)"*.

I7 noted that ergonomics training is often treated as part of general safety training rather than as a distinct discipline, despite its clear impact on productivity. I7 stated that *"I think the limitation is in ergonomics training"*. These findings contradict "work-as-imagined," where designers assume operators interact with well-designed systems as they are supposed to.

4.2 *Safety culture and perceived lean-safety-quality tensions*

Themes 2 indicate that safety is an organisational system-level concern rather than a matter of individual compliance, yet sometimes lean implementation often undermines the safe practices. I5 noted that "*The issue is not limited to individual behaviour it is fundamentally linked to the overall safety management system of the company*". I4 identified "normalisation of deviance" as a key concern, where operators repeatedly bypass safety protocols they perceive as unnecessary or low-risk, and in the absence of corrective action, such behaviour gradually becomes accepted practice.

The lean–safety tension was explicit. I6 stated: "*For lean, maybe it is insufficient focus on human factors because lean is focusing only on* *efficiency, not on the humans.*" I1 observed that lean-trained process developer may "*forget people*", compressing cycle times to reduce waste, which ultimately diminishes recovery time for operators and thus increases stress. I3 also noted that lean training is predominantly directed towards white-collar workers, who receive Yellow, Green, and Black Belt certifications, while shop-floor workers who often lack the understanding of lean philosophy receive comparatively little lean education. I3 described cognitive overload from tight scheduling as a major challenge, noting that "*cognitive load due to our tight time schedules*" is "*rather increasing*." This same time pressure also constrains training itself, as I3 stated that "*we need to be strict where to allocate our time resources at the moment, very, very, very strict*". I3 also observed that lean knowledge among shop-floor workers remains insufficient, stating that "*it's rather limited the information on knowledge on these aspects on (the) soft floor at least and also the basic engineering department*". I3 emphasised that lean training should prioritise frontline workers, noting that "*every (shop) floor worker should at least know the terms on lean manufacturing*" and that "*if you want to have the most impact, it has to go bottom up*". To address the cognitive burden, I3 suggested that "*AI based adaptive learning might be the key helping on this cognitive stress if it manages to free up the decision energy from the operator*".

4.3. *Human–technology interaction*

Theme 3 reflects is the dilemma of twin transition, where decades old machinery works alongside emerging automation.

I2 describes this dilemma by expanding on the challenges of working with ageing infrastructure, stating that "*the main issue is due to old machinery, old systems*" which are "*vulnerable for different kinds of errors*", with "*wear and tear that shows over 20-30 years*". Simultaneously, I2 noted that the organisation is exploring newer technologies, identifying collaborative robots as something "*we've been thinking of and trying to find ways to actually find good business cases and utilizations for*". This coexistence of legacy systems and emerging technology creates a dual training challenge where workers must navigate both outdated and novel interfaces.

I3 noted that shop-floor workers "*can be frightened, mainly due to fear of job loss from automation*" further cementing the psychosocial dimension of technology transitions.

4.4 *Issues with current training*

Theme 4 gives out a training gap current hands-on training focuses on theoretical aspects (using manuals) or peer to peer training, I6 described a 45-minute presentation and I7 a single-day training course with minimal follow-up. I5 describes the core deficiency: "*The training offered by organisations is also mainly theoretical, with very little practical content, which is a major issue... What is really missing is the opportunity for trainees to experience the real work environment*". I3 labels central challenge as individualisation: "*The hardest part is identifying training gaps, because people have specialised skills and know-how*".

Despite diverse organisational contexts, stakeholders converged on a consistent vision for future training. All participants agreed safe failure environments where learners can make decisions with visible consequences and no real-world risk. I2 found simulation-based training compelling precisely because of "*the possibility of making mistakes without any risk*". I5 proposed a pragmatic, scalable pathway: "*For organisations that do not have the technical capacity or the necessary budget, using an AI assistant or micro-learning, learning-by-doing modules is a more realistic solution*". Budget and time were universally identified as adoption barriers.

5. Discussion

Building upon the results of the thematic analysis, some preliminary requirements for the simulation platform can be derived. Overall, the results suggest that GenAI indeed has potential to support active learning in OSH, lean and quality management.

Regarding ergonomics, human factors and the changing workforce we note that the platform should account for differences in physical and cognitive capacity across age groups, consider psychophysical stress and mental health challenges arising from workload, and include ergonomic scenarios that demonstrate how design decisions affect worker wellbeing. The simulation scenarios should be intuitive and accessible to increase the likelihood of adoption among operators across all age groups. This is particularly important given the systemic gap noted by I4 and I1, who respectively observed that although industrial systems are intended to be operated by people, "*the human factors perspective [is] unfortunately... always not the case*" when these systems are developed, and "*(...) we know that the population is aging and we need to do a lot of automation in the future more than we are doing now, because there isn't enough qualified people for work. So, it means that the engineers who are designing those manufacturing methods for example, need to understand the capabilities of human being*".

About safety, quality and lean, the simulation platform should effectively integrate these three dimensions and demonstrate effects of decisions across them. Learners should be able to experience consequences of deviations and communication failures in a safe environment. This is necessary to take down what I4 identifies as a "*wrong feeling of being safe*", where workers mistakenly assume a lack of prior accidents justifies ongoing non-compliance.

The platform should also be able to simulate human-machine collaborative scenarios across different levels of automation, including situations that require failure recovery. An Industry 5.0 perspective, in which humans remain at the center of production processes should be reflected. This will help to build confidence that automation is intended to support workers and improve productivity rather than replace them. This can reduce fears of job loss and resistance and support technology adoption. The simulation should model realistic operator responses to technology transitions, including different levels of trust, fear of automation and troubleshooting under uncertainty. This aligns with I7's view that the *"human or individual is in the focus point"*, with technology augmenting human capability rather than removing the human factor.

The platform should be able to support learning scenarios of varying complexities, enabling scalable deployment for varying training needs. AI-driven adaptive difficulty and role-based personalisation (operator, supervisor, engineer, manager) can further individualize learning needs. Ultimately, the platform should replicate a space where, as I6 describes, a worker is enabled "*to make some decision and to make an error"* that might lead to a simulated accident but helps ensure that "*there are no consequences*" in the physical world after the training.

5.1 *Limitations*

This preliminary study has its limitations. The interviews are an initial sample conducted across three countries, and it's not balanced as larger proportion of experts are from Finland. This may introduce regional bias and affect the findings. The data collection relied solely on semi-structured interviews which primarily reflect subjective expert perspectives. The study only employs qualitative analysis and consequently the findings may be influenced by researcher interpretation despite the use of a structured process.

5.2 *Future Work*

The outcome of this study presents preliminary requirements that lay the foundation for developing a simulation-based training platform to support future workforce learning in the manufacturing industry. The step following the interviews is to develop a survey instrument to validate the qualitative findings presented in this study. The survey results are then further validated with expert workshops into the final socio-technical requirements for the simulation platform.

6. Conclusion

This paper presents an initial requirement engineering step toward a socio-technical simulation platform for manufacturing workforce education and training, motivated by the human-centric perspective of Industry 5.0. Using multi-country expert interviews and reflexive thematic analysis, we identified four recurring themes that reveal gaps in current training, particularly related to human factors, psychosocial strain, lean safety tensions, and human–technology transitions and translated these insights into actionable design implications for a novel simulation-based learning platform. Overall, the study provides a structured pathway from expert interview evidence to simulation requirements, establishing a foundation for subsequent validation and implementation phases of the 4SiM platform.

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