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A proposed framework using systems engineering to design human-centric manufacturing systems for novel products to reduce complexity and risk

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Abstract

The environment for powertrain production system engineers is changing radically. This initial prescriptive study proposes a systems engineering framework based on two previous case studies which are under review for publication concerning design of battery plants. The framework was developed based on ISO/IEC/IEEE 15288 standard using Concept of Operations and Model-Based Systems Engineering in a workshop setting, with a focus on visualisation to understand the practical and emotional needs of the humans in the system. The framework was validated by twelve senior project members.

Keywords: *industry 5.0, model-based systems engineering (MBSE), cyber-physical systems, design support system*

1. Introduction

Several driving forces are currently having a radical impact on the heavy truck industry. As a result, the manufacturing engineering community is faced by several unexplored challenges: a) the electrification of the end products that the production system is designed for, b) the Industry 4.0 implications for the equipment purchased to implement the production system, c) the effect of digitalisation on the engineering processes themselves and d), the introduction of Industry 5.0 (Hane Hagström, 2021). These challenges together suggests that complexity and risk might increase for industrial projects.

The combustion engine is more than 100 years old and has served as a legacy and a knowledge base for the entire powertrain engineering community for both product development and the design of production systems to manufacture these products. The production system that is now required to produce the electric drivelines possesses completely different characteristics and therefore the engineering community needs to acquire new types of knowledge. The dominant production processes for combustion engines have traditionally been forging steel, machining the steel with high precision and then manually assembling the steel components with external parts. With the arrival of electrification, the production characteristics of batteries will be more similar to those of the process industry. Production can become highly automated, with the main challenge being to reduce the size and cost of the battery (Manzetti & Mariasiu, 2015). When the Industry 4.0 factory arrives, it should be an intelligent environment where the pieces of production equipment can exchange information, trigger actions and control each other autonomously (Weyer et al., 2015). Machines will be performing more complex tasks and will require greater availability and uptime, which will impose significant demands on the design of the production system, on the acquisition of the machines and on the ability to maintain them (Hane Hagström, 2021; Li et al., 2019). The impact of digitalisation on the engineering process itself could be immense, with not only technological but also varied organisational implications (Eckert et al., 2020). With the introduction of Industry 5.0, the challenge increases further. Industry 5.0 is described "as the movement to bring the human touch back to the manufacturing industry" or to "leverage the unique creativity of human experts to collaborate with powerful, smart and accurate machinery" (Akundi et al., 2022). Industry 5.0 complements the techno-economic vision of the Industry 4.0 paradigm by emphasising the societal role of industry. With the radical changes in the eco-system for powertrain production system engineers, there is a need for methods and tools to manage complexity and risk.

Complexity is a characteristic of more than just a technical system being developed. It is often created by the interaction of people, organizations, and the environment that are part of the complex system surrounding the technical system (Sheard et al., 2015). While the production system in itself may not be considered complex as it should not generate patterns that cannot be understood or predicted, the development of the system is considered complex. Risk is defined as "the combination of the probability of an event and its consequence", and is generally used only when there is a least the possibility of negative consequences (ISO org, 2006). The purpose of this study is to propose a framework based on system engineering from a community used to managing uncertainty in a structured manner for the production system engineering community. The research question is therefore formulated as follows:

RQ1: How can system engineering methods be used to reduce complexity and risk in the design of an Industry 5.0 cyber-physical, human-centric manufacturing system for novel products?

This paper proposes a system engineering framework that can be used to design Industry 5.0 cyber-physical, human-centric manufacturing systems for novel products to reduce complexity and risk. The framework is based on two previous case studies which were submitted 2023 for publication. The studies explore the usage of systems engineering methods within manufacturing engineering covering a total of 122 persons in six workshops and two validation studies. The studies investigate how the use of Concept of Operations and Model-Based Systems Engineering can be used to design human-centric aspects in production systems of batteries.

2. Frame of reference

Efficient production systems are necessary for the realisation of products that fulfil customer needs and delivery requirements (Bellgran, 2003; Ito et al., 2022). Bellgran continues: "Designing a production system is a unique and complex task in which many parameters should be taken into account during the process of creating, evaluating and selecting the proper alternative". The importance of design, in particular, as an industrial activity and the increasingly complex and dynamic context in which it takes place have led to the desire to improve the effectiveness and efficiency of design practice (Blessing & Chakrabati, 2009). This also applies to the design of production systems. However, the process of designing the production system has received little academic attention and its potential for offering a competitive edge has largely been ignored (Bellgran & Säfsten, 2009). Islam et al. (2020) state that "there is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap". Vielhaber and Stoffels (2014) identified that in the academic world there is a greater focus on product development than on production development and that, in particular, methodologies and process models dedicated to production equipment have less scientific coverage than their product-oriented counterparts. Product development methods have been explored and adapted over many years. Within the systems engineering community (and the engineering design community), several methods have been developed to reduce complexity and manage risk by engineering institutions such as NASA (Kapurch, 2010) and INCOSE (2020), as well as key researchers in the field, for example Ulrich et al. (2020). Several of the methods are captured in the standard ISO/IEC/IEEE 15288 (2023). However, these methods have not yet been fully adopted by the manufacturing engineering community (Arista et al., 2023). Stark et al. (2017) state: "Today's manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity". Stark et al. continue: "In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity".

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System engineering aims to ensure that human-made systems are properly coordinated and functioning with a minimum of undesirable side effects, such as costly and disruptive consequences (INCOSE, 2015). System engineering is a structured, multi-disciplinary engineering approach for the development of complex technical systems, targeting a cross-disciplinary optimum within a given time frame and budget. When investigating to what extent the production system design community has adopted system engineering methods to understand human-centric factors, the main issues identified in the literature reviews from the previous case studies revolve around two gaps: 1) the lack of systematic and effective system engineering design methods in production system design and 2) the failure to include human factors in the production system design. Regarding the first of these problems, there are several issues relating to the methods themselves, such as the lack of systematic methods, the restricted abilities of the designers, the methods that do not encourage creativity and a small number of systematic ways to objectively evaluate the results. Moreover, the methods used today do not address the challenge of transferring the vast amount of knowledge within and between development teams. The consequences of these barriers include longer lead-times in projects as solutions are not reached quickly and directly, the excessive workload of engineers who frequently perform unnecessary tasks and less systematic ways to objectively evaluate the results of engineering and project cost overruns. A summary of research gap 1 is given in Table 1.

Table 1. Summary of barriers identified in literature to systematic and effective system engineering design methods in production system design

Category	Barrier
Skills	Designers' abilities are restricted
Knowledge transfer	A failure to address the challenge of transferring the vast amount of knowledge within and between development teams
	Difficulty in retrieving knowledge from previous projects
Ambiguity	Models are not clearly understood by designers
	Ambiguity regarding the responsibilities involved in each task because of a lack of commitment on the part of the functional departments
Creativity	Methods do not encourage creativity

The second barrier concerns the failure to include human factors in production system design. The literature can be summarised as tending towards over-simplification when describing model-based design, thus disregarding individual personality and skill profiles, since in complex systems, humans are often part of the complex system rather than simply users of the system. Engineering practices tend to address human considerations as an afterthought. In this regard, the literature identifies a failure of the engineering community to adequately present the value proposition of human system integration, where the human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk factor. At the same time, social developments in terms of workers' rights to varied and challenging work, good working conditions, learning opportunities, scope for decision-making, good training and supervision and advancement opportunities are in line with the initial value system in socio-technical design, even though the technology and the organisational structures in industry may change.

3. Research approach

Research in the engineering design field is not only understood as a pursuit of scientific knowledge; it also pursues the goal of introducing practical improvements in engineering design and practice. Ullman (2003) states that an estimated 85% of product development projects encounter problems concerning cost, time management or simply a failure to function as intended, which means that the design process is worth studying in order to identify areas for improvement. Among the most common methodologies applied is the design research methodology (DRM) presented by Blessing and Chakrabati (2009), which this paper has applied in the descriptive part of the study. To understand how system engineering methods can be used to design a complex cyber-physical production system in preparation for Industry

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5.0, an initial prescriptive study was designed which aims to describe the intended support. The model used is based on the systematic prescriptive study process, where the first two steps are covered in an initial prescriptive study.

The case company is a global actor in the transport solution business with about 100,000 employees worldwide. Its portfolio includes several brands, together with a variety of vehicles, from excavators to buses and trucks. The company consists of several organisations, all of which interact on an operational level. It has factories in 18 countries. In addition to its production sites, its global industrial operations include several product development centres and several parts distribution and logistics centres. Furthermore, it has assembly plants operated by independent companies at ten locations around the world. This case study covered a project to set up a new production line for a new novel product using production processes previously unknown to the engineering departments. The author followed the production management part of a battery assembly plant project for 18 months and the battery cell plant for six months. The plan was to establish a battery cell production plant about 40 kilometres away from the battery assembly plant. The battery assembly plant is located on the site of an existing production facility for combustion engines and can take advantage of the large-scale, well-established industrial set-up. The battery assembly plant will distribute the batteries to the truck plants in the industrial system of the case company. The industrial flow is described in Figure 1, with the focus of this study circled.

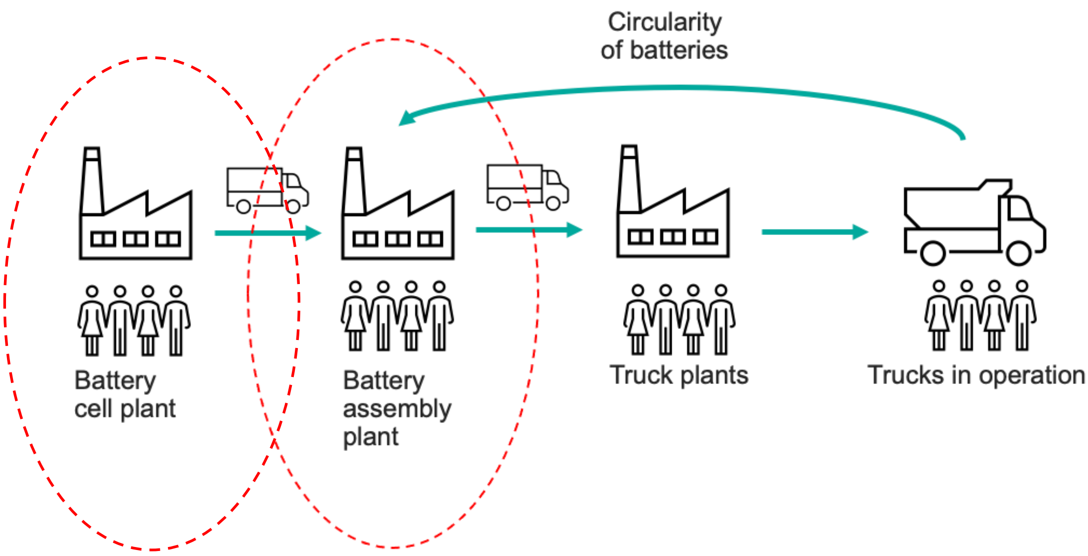

Figure 1. The planned industrial flow in the battery production system project with the focus of this study circled

The project aims to set up a production system for battery assembly and distribution, including a circular flow of used batteries and the remanufacturing of these batteries.

4. Results

Literature reviews from the two preceding studies have identified two barriers concerning the extent to which the production system design community has adopted system engineering methods to take into consideration human-centric factors (Bellgran (2003), Bellgran & Säfsten (2009), Hane Hagström (2021), Islam et.al. (2020)), Vielhaber & Stoffels (2014):

- Lack of systematic and effective system engineering design methods in production system design with the main barriers being: a) A failure to address the challenge of transferring the vast amount of knowledge within and between development teams, b) Difficulty in retrieving knowledge from previous projects, c) Models that are not clearly understood by designers, d) Ambiguity regarding the responsibilities involved in each task because of a lack of commitment on the part of functional departments and e) Methods that do not encourage creativity
- Failure to include human factors in the production system design

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Earlier case studies exploring the usage of systems engineering methods within manufacturing engineering covered a total of 166 persons in six workshops and two validation studies. Findings from these studies are that the focus of the engineering department had been:

- More equipment-oriented than production system-oriented
- More equipment-oriented than human-centric

Out of the gaps identified in previous studies, nine were targeted to be addressed as described in the intended impact model of the developed framework in Table 2.

Table 2. Intended impact model of the developed framework

Problem statement: Develop a systematic and effective framework to help experienced manufacturing engineers to take into consideration human-centric factors when designing cyber-physical production systems for novel products.	
Requirement list:	
	System view
R1	The framework should help to manage complexity
R2	The framework should help to manage risk
R3	The framework should offer a systematic and effective system engineering design method for use in production system design
R4	The framework should focus on the system, not only the equipment
	Human-centricity
R5	The framework should help to include the human factors, alongside the focus on the equipment
	Design methods
R6	The framework should help to develop designers' abilities
R7	The framework should address the transfer of knowledge within and between development teams
R8	The framework should support models that are clearly understood by designers
R9	The framework should encourage creativity

On the basis of the requirements developed in the intended impact model, the main functions of the framework are described in Table 3.

Table 3. Main functions based on the intended impact model of the developed framework

Requirement list:	
	Main function
	System view
R1	Visualisation of the system overview to give a collective understanding of what the system will do. This allows complexity to be understood by all parties in the project
R2	Visualisation of the system overview to give a collective understanding of what the system will do. This enables the main risks to be identified by all parties in the project
R3	A usable concept for the engineers' working methods when designing cyber-physical, human-centric manufacturing systems for novel products to reduce complexity and risk
R4	Visualisation of the system overview to give a collective understanding of what the system will do. This allows the equipment to be seen in a context and enables decisions to be taken based on a system view
	Human-centricity
R5	Understanding the practical and emotional needs of a person in the system, using prototypes or physical models to explore possible ways of achieving goals
	Design methods
R6	Sufficiently instructive to enable engineers to increase their competence
R7	Using models that can be understood by other functional teams
R8	Using models that can be understood by the designers within the team
R9	Creativity is encouraged in the different ways of working

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On the basis of the results of earlier case studies, the framework is selected to be developed in accordance with the ISO/IEC/IEEE 15288 (2023) standard using the concept of operations and model-based system engineering in a workshop setting, with a focus on visualisation, understanding the practical and emotional needs of a client and using prototypes or physical models. These findings were identified in collaboration with the engineers and cross-functional teams. The aim was to create a high-level requirements specification at an early stage for the generation of potential solutions. Based on the teams' evaluations, it would then be possible to generate solution-specific requirements. The combination of earlier studies allowed the problem statement to be generated and this was broken down into the main functions. A framework was then developed, which is shown in Figure 2. The framework could potentially be used in several different applications, but as the study referred to a specific aim the framework is only positioned towards this aim.

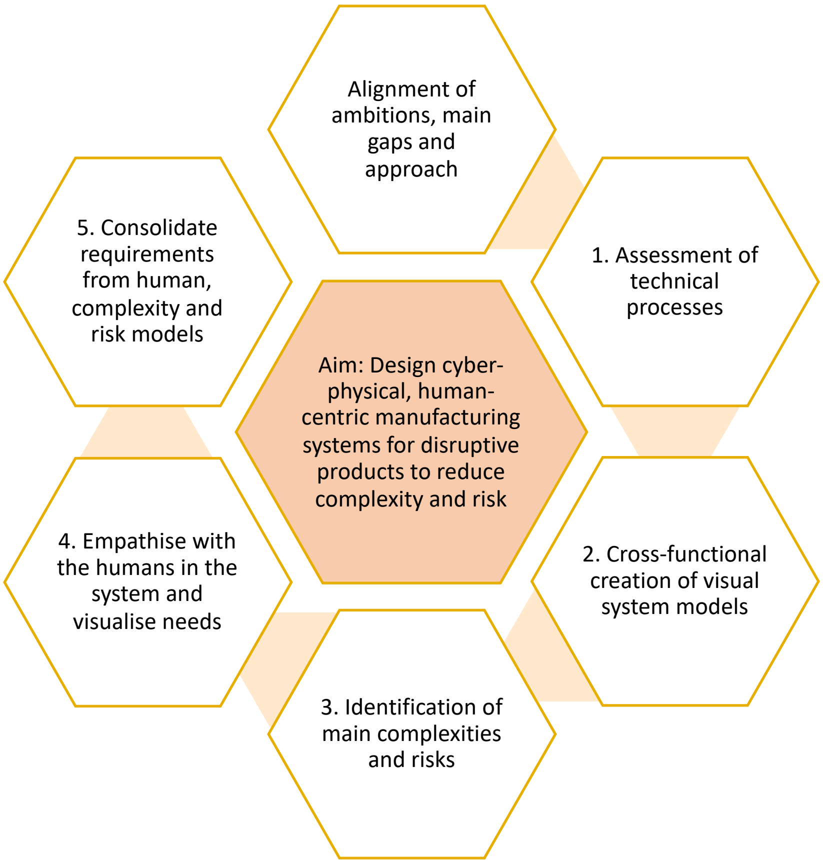

Figure 2. Proposed system engineering framework for the design of cyber-physical, human-centric manufacturing systems for novel products to reduce complexity and risk

For any successful project, the initial alignment of the aims, main gaps and approach is crucial, but this is not developed further in this paper. The intended support description for each stage is given in Table 4.

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Table 4. Intended support description for each stage of the developed framework

	STAGE 1: TECHNICAL PROCESS LEVEL	STAGE 2: VISUAL SYSTEM MODELS	STAGE 3: RISK AND COMPLEXITY	STAGE 4: EMPATHISE WITH HUMANS IN THE SYSTEM	STAGE 5: CONSOLIDATE
Functionality fit	R1, R2	R1, R2, R3, R4, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R3
Goals and objectives of the support	Collective high-level understanding of the current maturity of the project as a whole	Collective high-level understanding of what the system will do and how it works	Collective understanding of complexity and risk	Inclusion of human aspects in the production system design.	A usable concept for the engineers' ways of working when designing cyber-physical, human-centric manufacturing systems for disruptive products to reduce complexity and risk
Its elements	Assessment of technical processes	Visual models in drawings and/or films	Indication of main risks in the visual model, mapped to the driving sub-system and addressed	Visual personas with needs and problems which are documented and collected to the requirement list	Collection of input to the requirement list from the visual models ConOps, OpsCon and personas requirements
How it works	Alignment workshop to understand the maturity of each element and the system as a whole	Creative cross-functional workshops where the system is mapped	Creative cross-functional workshops were risks and complexities are aligned upon	Creative cross-functional workshops creating personas to empathise with the human in the system, state their needs and problems and break down to concepts	Consolidation of the previous work and iteration
The underlying concepts	Technical Processes	Concept of Operations, Operations Concept	Technical Processes, Concept of Operations, Operations Concept	Model-Based System engineering	
Theory	ISO/IEC/IEEE 15288 (2023) INCOSE Handbook				

4.1. Validation

The proposed framework has been tested with validation follow-up in the earlier case studies. The framework was also validated in a workshop covering Stage 1 to Stage 4 with the battery cell plant management team, a total of twelve cross-functional managers. The participants were asked to answer three questions:

- Does this way of working provide support with managing complexity? If so, in what way?
- Does this way of working provide support with managing risk? If so, in what way?
- Does this way of working provide support with implementing Industry 5.0? If so, in what way?

All the participants answered yes to the questions regarding support. Some of the comments concerning the management of complexity included: "The early visualisation helps you structure the work and ask yourself the right questions", "A good way to get an overview of the process and start to discuss complexities when we are all looking at the same picture", "The complexity becomes tangible when we as a team describe what we want to achieve", "We were all able to brainstorm together and assess the same issue/situation from different points of view", "Pictures are always easier to relate to and team discussions provide leverage", "Yes, everybody contributing and being part of the discussion creates a structure in itself", "This gets us all aligned and helps us to learn. When things are moving quickly in all areas, the need for these kinds of workshops increases to help us to manage complexity".

Some of the comments about the management of risks were: "The early visualisation forces us to align and that means we can mitigate many of the risks", "Breaking down the questions and putting the focus on a person in the work environment makes it easier to understand the risks with the focus on the human aspects", "Expressing the complexity and putting it into words helps you understand the risk", "We were able to share all our previous experiences of failure related to running a plant in the operations team. We also discussed measures we could take to overcome the problems", "Yes, we can identify the risks early – the earlier the better", "It helps us to understand the different areas and identify things we have not addressed".

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On the subject of the implementation of Industry 5.0, a concept defined by the company, the comments were: “The visualisation helps you to solve the obvious issues, but the environmental and human dimensions help you to move from Industry 4.0 to Industry 5.0”, “This method brings up questions during team discussions and it creates possibilities for discussing complex issues”, “This is a good start but I need to understand and refine Industry 5.0 in more detail, so that we can make it more understandable and easier to implement”, “Yes, we were trying to think about solutions not only in the traditional ways, but also considering new technologies such as AI”, “Yes, this gives you a fairly clear method for addressing different dimensions of the concept”, “By bundling our vision across three relevant perspectives, we can create a base for our overall storyline and employer branding so that we can attract young people and professionals in mid-career to the industry and to our company”.

5. Discussion

The tests of the framework have given rise to new demands on IT and produced positive feedback on the ways of working. Working with visual models and emphasising their importance in promoting understanding among all the actors is a new approach for the organisation. The case company is working predominantly with document-based engineering, which makes it difficult for the entire team to grasp the full view of the system. Another new approach in this project is that all the actors in the production system are invited to participate. Normally the engineering department invites “stakeholders” one by one. Traditionally the human aspects have not been specifically highlighted as they are in this project, which makes use of personas. The validation session highlighted the fact that this seems to be highly appreciated by the project members. They find it rewarding to see the project as a system that they own together, rather than simply delivering just their piece of the puzzle. The findings from the study are promising when it comes to addressing the goals of managing complexity and risk in the context of implementing Industry 5.0. The generalisability can be more difficult to demonstrate. On the other hand, design research is important in the very early stages of development where the concepts are still to be developed. With regard to managerial considerations, it is crucial to challenge the current ways of working and make sure that the organisation's methods and skills are up to date and can deliver the industrial systems of the future. These systems should support a resilient production system not only over time, but also within the constraints of the planet and encompassing the full scope of a human-centric approach. Additionally, one can argue that to develop a human-centric system one should apply human-centric design methods and not using a techno-centric design method. Persuading the engineering community to use systematic, state-of-the art human-centric design methods will require a great deal of management and organisational ability.

6. Conclusion and further research

Several driving forces are currently having a radical impact on the heavy truck industry. As a result, the manufacturing engineering community is faced by several unexplored challenges. These challenges together suggests that complexity and risk might increase for industrial projects. In the academic world there is a greater focus on product development than on production development and that, in particular, methodologies and process models dedicated to production equipment have less scientific coverage than their product-oriented counterpart. Together this suggests that there is a need for development of frameworks that support manufacturing system design engineers based on empirical studies, specifically targeting human-centric manufacturing systems, which was the aim of this study.

The framework combines several system engineering methods for designing Industry 5.0 cyber-physical, human-centric manufacturing systems for novel products to reduce complexity and risk. The framework proposes a combination of systematic design methods and cross-functional creativity with visual system models. It targets the early stages of a project: the specification and concept development phase. Studies within the case company showed that the developed framework had produced promising results, both by identifying new requirements and by using feedback from interviews with the project members about the way of working. By combining the system engineering methods of technical process assessment, concept of operations, operations concept, design thinking and model-based system engineering, the framework has placed new demands on IT that had not been identified in the traditional models used by the case company. The framework has also received promising feedback from validation workshops with a total of 134 people: twelve people for this paper and 122 people in the earlier studies. When investigating the extent to which the production system design community has adopted system engineering methods to take into consideration human-centric factors, the main issues identified in the literature reviews from the previous case studies revolve around two gaps: 1) A lack of systematic and effective system engineering design methods in production system design and 2) A failure to include human factors in production system design. The framework can address these issues as it proposes a systematic system engineering design method for use in production system design which supports the inclusion of human factors. However, the problems with the effectiveness of the methods have not yet been evaluated, as the project still has a few more years to run. Further research is proposed that will focus on the implementation of frameworks in system engineering design methods in production system design, in particular for novel products, where a large amount of new knowledge needs to be developed. In addition, further research on the integration of human factors into production system engineering design is required to prepare for future generations of workers. Finally, there is a need to explore further how the production system design engineering community can learn from the product development community and to identify whether these methods would have any actual impact on project cost and lead-time overruns, the workload of engineers and better production systems in terms of resilience, sustainability and human factors.

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