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Using visual requirements modeling to design human-centric manufacturing systems for novel products – A comprehensive predictive case study

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Abstract

Efficient production systems are necessary for the realization of products that fulfil customer needs and delivery requirements. However, the process of designing the production system has received little academic attention and today's manufacturing system design processes and architecture are still based on traditional engineering methods. This study covers a case study using visual requirements modeling for the design of a production system for a new product. A comprehensive prescriptive study was designed combined with attempts to verify the methods used. A total of six workshops, development of models to define requirements to select concepts, and two validation studies are documented. A total of 166 persons participated, and up to 15 persons participated in the validation workshops. The analysis shows that the method addressed several of the gaps identified in literature: (1) the lack of systematic and effective systems engineering design methods in production system design, and (2) the lack of inclusion of human aspects in the production system design. The gaps in the effectiveness of the methods remain to be fully evaluated, as the project is still running and will not be concluded until 2025. Recommendations for future work include exploring further the management mechanisms of systems engineering, which type of competences does the future engineer need and how production system design engineers can learn more from other disciplines.

KEYWORDS
human-centric design, Industry 5.0, systems engineering design, visual requirements modeling

1 | Introduction

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."[1] Industry 5.0 complements the techno-economic vision of the Industry 4.0 paradigm by emphasizing the societal role of industry. The core values of Industry 5.0, as described by Breque et al.,[2] are human-centric, resilience, and sustainability. The enabling technologies, as described by Villani et al.,[3] are individualized human-machine interaction enabling technologies that combine the strength of humans and machines on so called cyber-physical manufacturing systems.[4] Sustainable innovation must go hand in hand with maintaining and increasing industrial competitiveness[5] and manufacturing industries specifically need to embrace and adapt to the digital and circular transformation.[6]

Efficient production systems are necessary for the realization of products that fulfil customer needs and delivery requirements.[7,8] Bellgran et al. continue: "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." With the impacts in manufacturing industry, decision-makers must be enabled to successfully navigate the action field of radical and incremental innovations and local and global value creation.[5] The importance of design, in particular as an industrial activity and the increasingly complex and dynamic context in which it takes place, has led to the desire to improve the effectiveness and efficiency of design practice.[9] This also applies to the design of production systems. However, the process of designing the production system has received little academic attention, ignoring its potential for gaining a competitive edge.[7,10] Islam et al.[11] 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[12] identified that in academia there is a larger focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts.

Product development methods have been explored and adapted over many years. Within the systems engineering (as well as the engineering design) community, several methods have been developed to reduce complexity and manage risk from engineering institutions such as NASA[13] and INCOSE[14] as well as key researchers in the field, for example Ulrich et al.[15]. However, these methods have not yet been fully adopted by the manufacturing engineering community.[16] Stark et al.[17] 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."

This article covers a case study using visual requirements modeling to the design of a production system of a new product. This method is used to develop needs and requirements on a system, as described in ISO/IEC/IEEE 15288,[18] in Figure 1.

The research questions are formulated as:

RQ1: How can visual requirements modelling be used to reduce risk in design of a new battery manufacturing system preparing for Industry 5.0?

RQ2: What can be learnt by using visual requirements modelling in design of a new battery manufacturing system preparing for Industry 5.0 to reduce complexity and risk?

2 | FRAME OF REFERENCE

Systems 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. The increase in complexity of modern systems result from the number of system elements and the amount of information and knowledge needed to describe the system.[20] Designing manufacturing systems requires the design of relevant manufacturing artefacts while following a certain design and operations framework (DesOps)[6]; Systems engineering is frequently associated with document-based engineering.[21] To overcome the challenges of document-based systems engineering, there is a movement toward more formal modeling and integration of different views into a consistent system model. For example, in INCOSE, a recommended approach is to model information about system requirements, design, analysis verification, and validation activities, and serves as a central repository for design decisions (INCOSE).[14] Models are central to documenting results, applying simulations, analyzing different solutions, and transferring knowledge in different engineering activities. When engineering modern systems involving services and subsystems from various engineering domains, different perspectives have to be addressed resulting in a heterogeneous model landscape.[22] Model-driven engineering focuses on the development of systems using models as a center part of the development process.[23] To develop a system model, four elements are essential: the system model, a modeling method, a modeling language, and a modeling tool.[24]

A literature review performed by Berschik et al.[21] on the usage of model-driven engineering in the engineering design community showed that of 56 studies that were selected for analysis, only three of them addressed the linkage of system and production.

Several researchers have addressed the need to extend the focus of the design of industrial systems to the whole sociotechnical system.[25–31] They claim that human actors are often greatly simplified in engineering design, thus disregarding individual personality and skill profiles. Jones et al.[32] identify the actors in Industry 5.0 manufacturing systems as human, organizational, and technology-based agents. In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current system engineering practices tend to address human considerations as an afterthought.[29] Furthermore, as stated by van Erp and Rytter,[6] structured design procedures for manufacturing systems supporting the circular and digital transformation seem to be inadequately discussed so far.

The objective of human-centered model-driven systems engineering is to incorporate human actions in multiple viewpoints.[29] In today's systems engineering practice, the integration of humans into production systems is only pursued retrospectively, that is, after the architectures have already been specified and designed.[28] The authors continue: "Model-based development offers the potential to improve the integration of human needs into early system design." The human is the most important and unique element within a system, as well as the

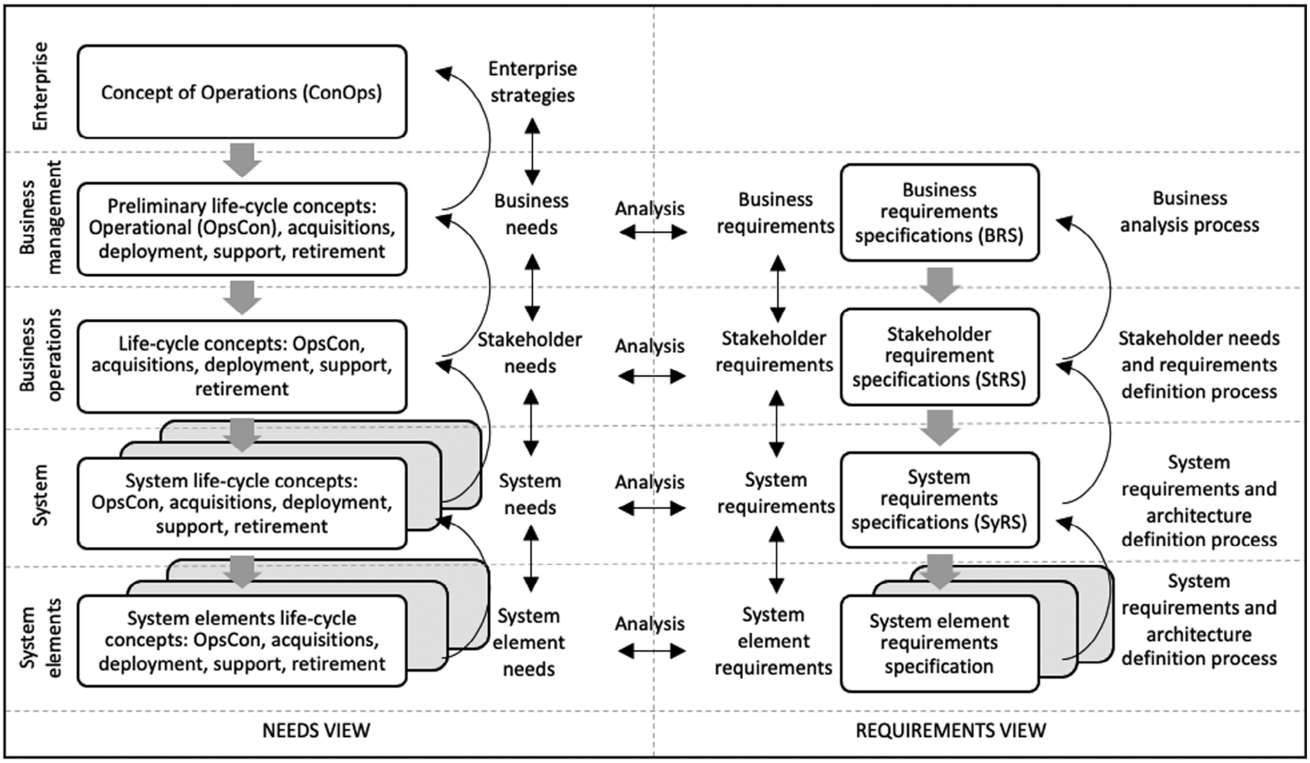

FIGURE 1 Transformation of needs into requirements. Adapted from INCOSE Handbook.[19]

weakest link and potentially the highest risk,[33] and should therefore be included and appropriately modeled.[29]

3 | RESEARCH APPROACH

Several authors have discussed the need for design research to be scientific (Blessing and Chakrabati[9]) and how to achieve a sufficiently scientific level in this type of research. Research in the engineering design field is not only understood as a pursuit of scientific knowledge, but it also pursues the goal of practically improving engineering design and practice.[34] Ullman[35] states that an estimated 85% of product development projects encounters problems in cost, time management or by simply not functioning as intended which means the design process is worth studying to identify improvement areas.

3.1 | Framework for design research methodology

To counter the critique of the scientific qualities of engineering design research, several researchers have suggested research approaches to guide researchers in the field. Among the most common methodologies applied is the design research methodology (DRM) presented by Blessing and Chakrabati,[9] which this study has applied for the descriptive part, as described in Figure 2.

The DRM by Blessing and Chakrabarti[9] is divided into four research stages: research clarification, descriptive study I, prescriptive study, and descriptive study II. This study is focusing on the prescriptive study phase. To be able to answer the research questions, literature studies supported by prescriptive case studies have been selected as research approach. The case studies have included both qualitative and quantitative research methods.

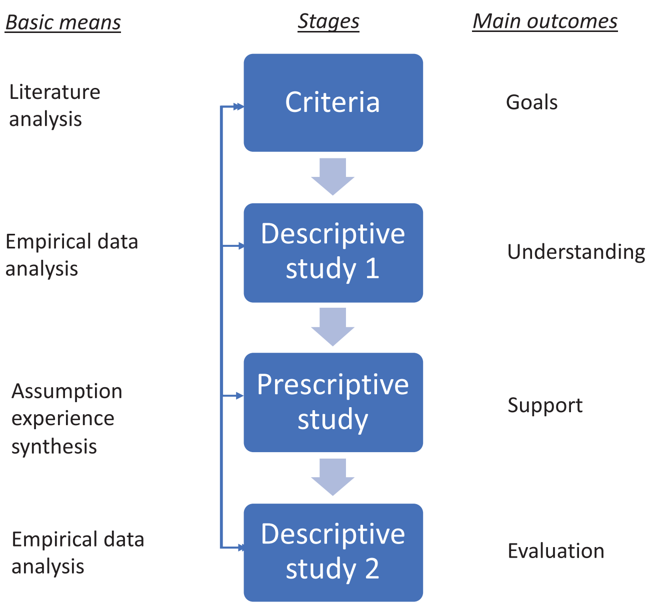

FIGURE 2 The DRM framework, from Blessing and Blessing and Chakrabati.[9]

3.2 Literature study

A literature study was performed during the research process. The method of reviewing the literature varied throughout the process. Three databases were used: Scopus, Web of Science, and Access Science with complements from Google Scholar. The keywords were combined into search strings with Boolean operators, together with a summary of the number of records that each search string produced, with results limited to peer reviewed full text and the scope of the years 2015–2023. Snowballing was used in several instances. Since the same search strings were used in more than one database, duplicates occurred in the searches in the different databases. Where the titles were relevant, the abstract and keywords were read and added to the list of studies to be read in full. The main criterion for exclusion and inclusion was a connection to manufacturing industry or engineering. Articles that were focusing on pure technology, modeling languages, and existing manufacturing systems were excluded. In addition, only published articles, conference papers, books, and book chapters were included, and another criterion was a clear link to the research questions. An important note is that the latter criterion involves a risk of bias in terms of subjectivity, since it relies on the researcher's interpretation of whether a study is connected to the research question. Twenty-five studies were considered relevant and of sufficient quality for further analysis.

3.3 The case company

The case company is a global actor in the transport solution business with about 100,000 employees world-wide. Several brands are represented in the portfolio and a variety of vehicles, from excavators to buses and trucks. The company is set up by several organizations who are all interacting on operational level. The company has factories in 18 countries. In addition to its production sites, its global industrial operations include several product development centers and several part distribution and logistics centers. Furthermore, there are assembly plants operated by independent companies at 10 locations around the world. This case study was performed on a project to set-up a new production line for a new disruptive product with production processes previously in-known to the engineering departments.

The author followed the production management part of a battery assembly industrial plant project for 18 months. The plan is to establish a battery cell production plant about 40 km from the battery assembly plant. The battery assembly plant is located within the compound of the already existing production facility of combustion engines, with the ability to take advantage of the vast and highly 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 3, with the focus of this study circled.

The project aim is to set up a fast-paced high-volume production system for battery assembly and distribution, including circularity flow of used batteries with remanufacturing of these.

3.4 Comprehensive prescriptive study

To understand how the visual requirements modeling can be used to design a complex cyber-physical production system prepared for Industry 5.0, a comprehensive prescriptive study was designed combined with attempts to verify the methods used. The study is performed as a Comprehensive PS, as it results in a support that is realized to such an extent that its core functionality can be evaluated, compared to Initial PS, which describes the intended support, and a Review-based PS, which evaluates the developed support without the researcher being involved. For this Comprehensive prescriptive study, the design guidelines and methods applied were primarily selected from design thinking and model-based system engineering approaches. To grasp many perspectives from the organization, not only the engineering dimension but also cross-functionality was identified as key to develop the demands and requirements from the stakeholders to the system.

The model used is based on the systematic prescriptive study process, described in Figure 4.

3.5 Workshop design

Workshops were selected as research approach to be able to capture the cross-functional aspects to build a common understanding of the system, as recommended by literature.[36] The workshops are described in terms of number of participants, theme, organizations represented, organizational hierarchy, and the output from each workshop. Table 1 summarizes the workshops held with the number of participants, theme of each workshop, organizations represented, and organizational hierarchy.

4 RESULTS

The results from the comprehensive predictive study are presented as follows.

4.1 Literature review

The literature review identified two main barriers: (1) the lack of systematic and effective systems engineering design methods in production system design, and (2) the lack of inclusion of human aspects in the production system design.

Regarding the first barrier, there are several issues regarding the methods in themselves, such as the lack of systematic methods, that designers' abilities are not developed enough, that the methods do not encourage creativity, and that there are less 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. Other issues associated with this gap regard the effectiveness of engineering; examples of

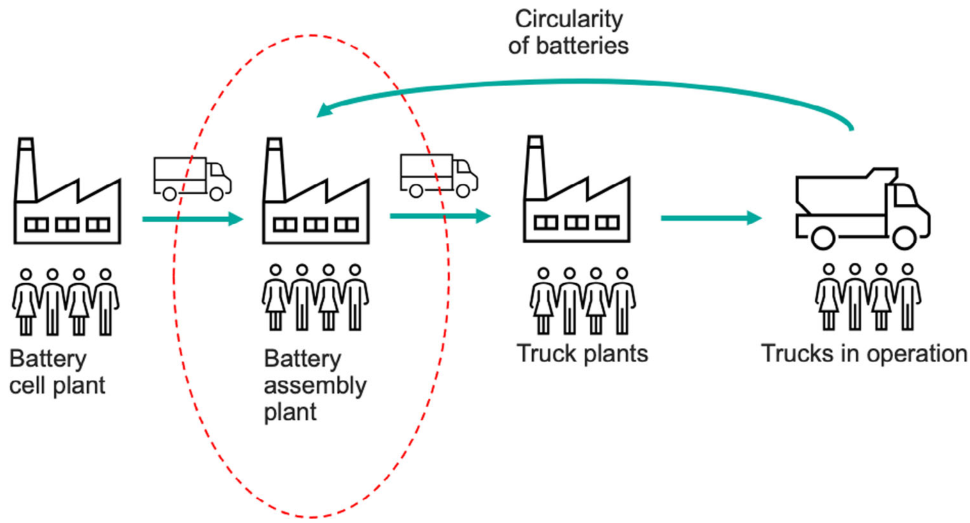

FIGURE 3 The planned industrial flow in the battery production system project with the focus of this study circled.

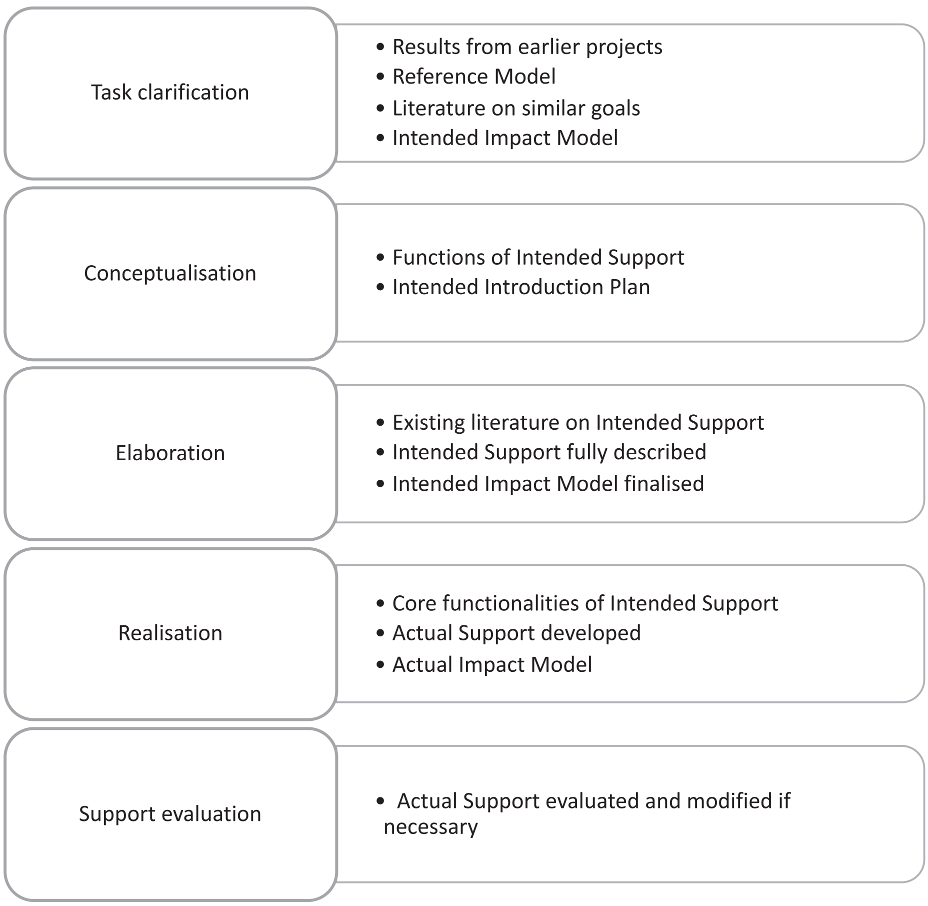

FIGURE 4 Main steps in the prescriptive study stage, from Blessing and Chakrabati.[9]

this include longer lead-times in projects, as solutions are not reached quickly and directly, work overload of engineers, work overload of designers and engineers who frequently perform unnecessary tasks, models not being clearly understood by designers, project cost overruns, difficulty in retrieving knowledge from previous projects, and ambiguity regarding task-related responsibilities due to insufficient commitment of functional departments. The second barrier covers the lack of inclusion of human aspects in production system design. The

TABLE 1 Summary of workshops held with number of participants, theme of each workshop, organizations represented, organizational hierarchy, and output from workshop.

Workshop #	Theme	Organizations represented	Organizational hierarchy	Output from workshop
1 (22 p.)	Alignment reference group	Production, Logistics, Engineering, Logistics Engineering, Maintenance, Planning, IT	Sr leadership, middle management, project members	Co-created and shared visual models of alignment in requirements from the system
2 (44 p)	Empathizing with the people in the system	Production, Logistics, Engineering, Logistics engineering, Maintenance, Planning, IT, operators, maintenance technicians, circular operations	Sr leadership, middle management, project members, operators	Co-created and shared visual models of six personas identified with their requirements on the future system
3 (22 p)	Management aspects of preparing, ramping up and running production	Production, Logistics, Engineering, Logistics engineering, Maintenance, Planning, IT	Middle management, project members	Co-created and shared three descriptions on the most important aspects from management
4 (28 p)	Staff functions, humans in the system	Quality, engineering, maintenance, logistics	Middle management, project members	Co-created and shared five personas identified with their requirements on the future system
5 (38 p)	Digital and physical flow	Customers and suppliers in the end-to end flow, Production, Logistics, Engineering, Logistics Engineering, Maintenance, Planning, IT	Middle management, project members	Co-created and shared visual models of the main risks in the end-to-end digital and physical flow
6 (12 p)	Digital flow deep dive	Production, IT, Engineering	Middle management, operators	60 new demands from production to IT

literature can be summarized as tending toward over-simplification when describing humans in the system, 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 sociotechnical design, even though technology and organizational structures might change in industry.

4.2 | Task clarification

In June 2022, the initiative started up with sessions with the future production manager to understand the situation in the projects and the challenges going forward. The overarching assignment was to create a production plant, producing a disruptive product that was not finally designed, with processes not known before and with the aim to align to Industry 5.0. The challenges were identified and summarized as (a) creating a human-centric system, (b) establishing a management system for preparing, ramp-up and running production, and finally (c) setting-up the digital and physical flow. To mitigate the challenges, proposals of methods going forward were presented and visual requirements of modeling were selected. Results from earlier projects had shown that the focus from engineering had been more equipment oriented than production system oriented, which was targeted to address in this project, and that even if the focus has been on equipment installations, there were still problems in production stemming from design. The hypothesis in this stage is the intended impact model in Figure 5.

4.3 | Conceptualization

From the task clarification documented in the intended impact model, the intended support description was generated. The intended support description describes the support in terms of the need or problems addressed, the goals and objectives of the support, its elements, how it works, the underlying concepts, theory, assumptions, and rationale, and how it is to be realized. This was generated together with a reference group at the case company from brainstorming. A workshop

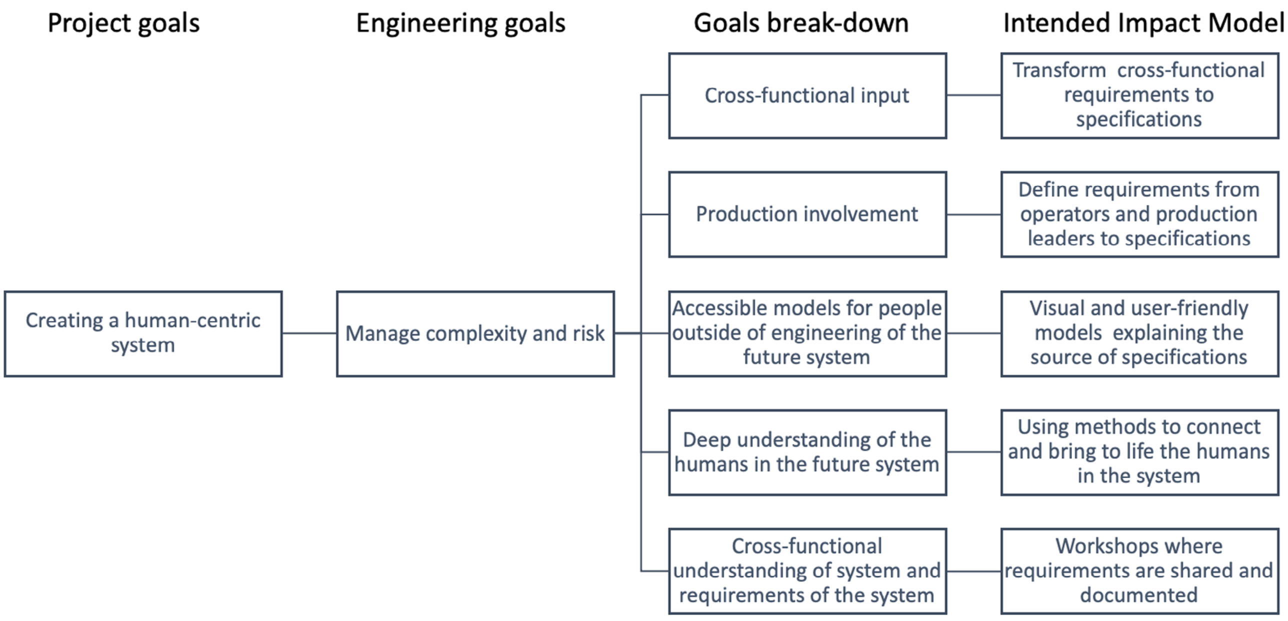

FIGURE 5 Logic of development of intended impact model for the comprehensive predictive study.

TABLE 2 Intended support description.

Intended support components	Intended support description
Assumptions and rationale	• Provide methods for engineering to develop a human-centric production system
Need or problems addressed	• Support to manage complexity • Support to manage risk • Support the implementation of Industry 5.0
Goals and objectives of the support	• Deep understanding of humans in the system • Aligned cross-functional understanding of the system
Its elements	• Workshop format • Persona guidelines • Participation list • Documenting methods • Documenting tools
How it works	• Cross-functional workshops • Production involvement • Documentation of requirements • Transformed into visual models in different levels
The underlying concepts	• Accessible visual system models for the entire organization • Bring the humans in the future system to life
Theory	• Systems engineering • Production system development • Design thinking • Visual modeling
How it is to be realized	• Management commitment • Training sessions on theory and underlying concepts • Access to modeling experts • Follow-up

model was developed focusing on cross-functionality, requirements documentation, visualization, and common system understanding. From literature, visual requirements modeling and design thinking were studied and adopted. The intended support description is described in Table 2.

4.4 | Elaboration

The intended impact model and intended support description were iterated, and an intended introduction plan was generated to consist of six workshops with various actors invited as seen in Figure 6.

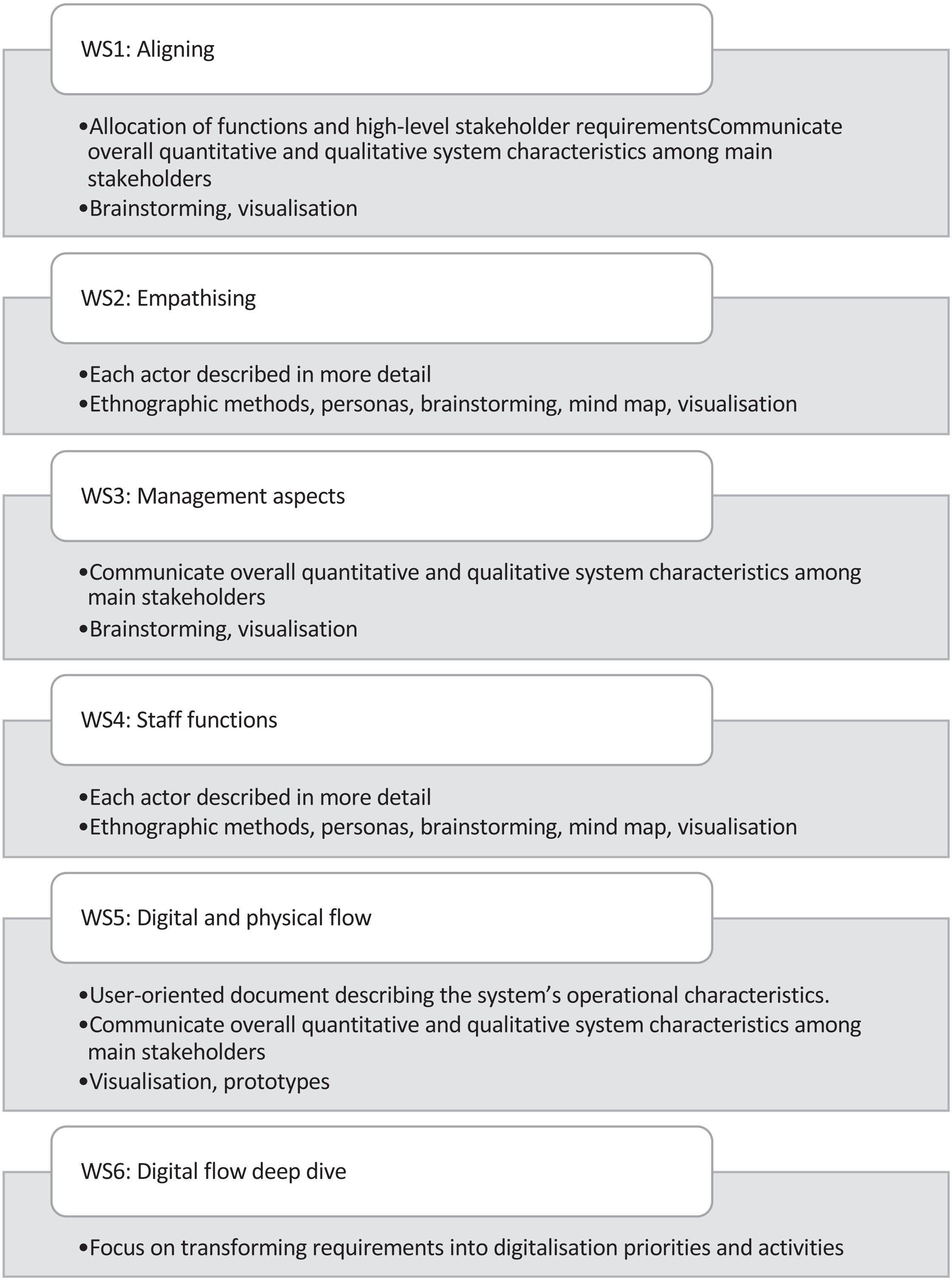

FIGURE 6 Elaborated intended support description with intended implementation plan.

The workshops were designed to be between 3–4 h long and with the format as described in Figure 7.

The focus of the indented design support is to ensure how to get a satisfactory quality of input from all actors in the future system, hence the documentation and visualization of the models were to be performed by the researchers and experts.

4.5 | Realization

In the realization phase, the core functionalities of intended support, actual support developed, and actual impact model are elaborated upon. From the workshop results where the input was collected, the models of requirements and specifications were created. As the

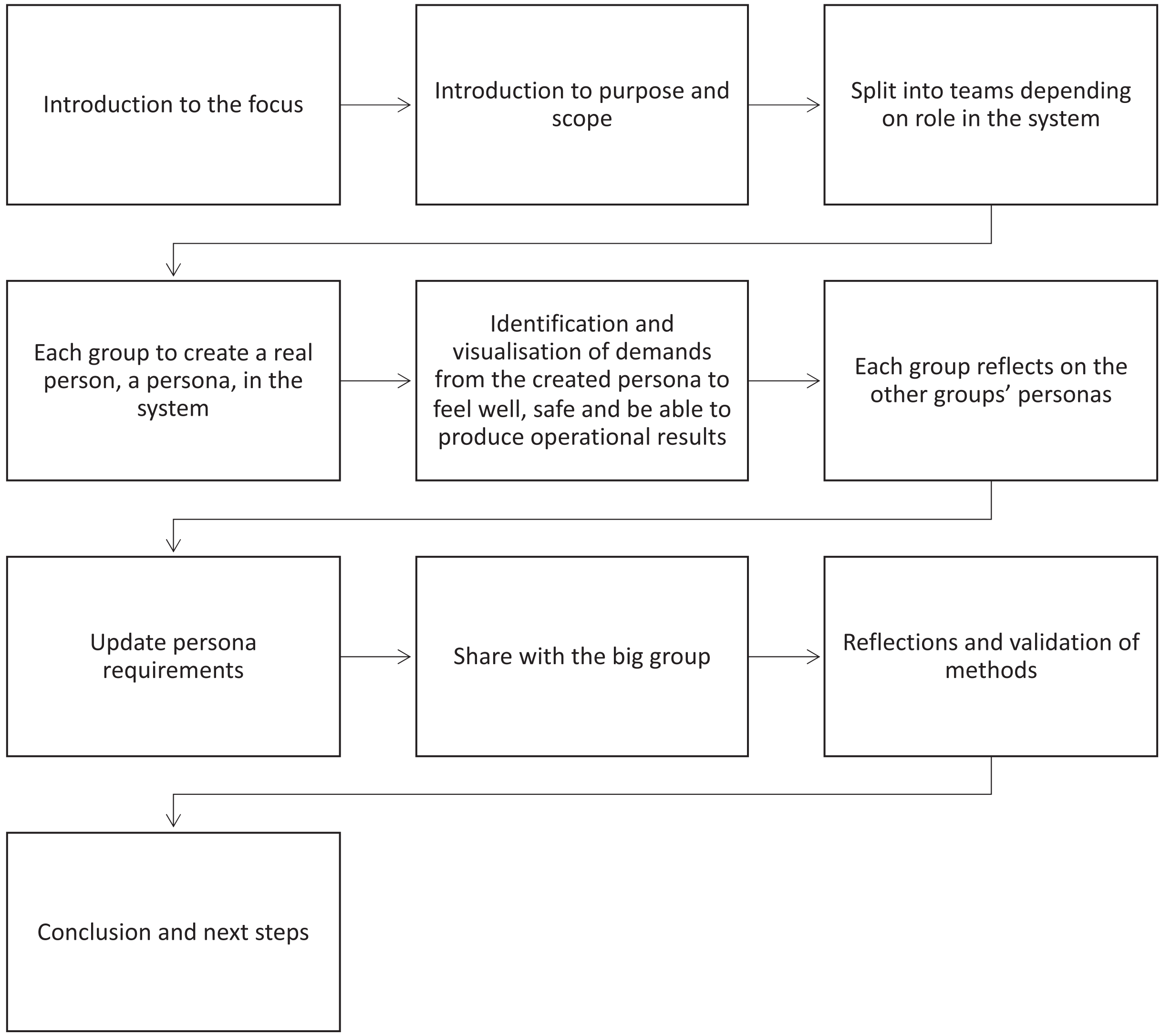

FIGURE 7 Workshop design for the six workshops.

participants ranged from little to expert knowledge about engineering, the decision was to use accessible and as easy tools as possible. The modeling method was selected to be mind-maps, the modeling tool MindManager, which does not require any specific modeling language.

The participants documented the requirements in drawings in the workshops and the researchers documented them in the software, starting from the human in the cyber-physical production system. From the workshops, the requirements were organized in clusters and developed further within that category. The lines between some of the requirements indicate dependencies. The model is described in Figure 8.

As the next step the model was used by the project to tag each requirement indicating which sub-system the requirement was influenced by. The sub-systems were Training system, IT system, Production System, Improvement system, Facilities system, and Maintenance system. A zoom in on the model is visualized in Figure 9, with the tags per each requirement family.

These tags are used to organize the requirements to the correct team as can be seen in Figure 10.

4.6 | Support evaluation

To confirm that visual requirements modeling development was verified as relevant for engineering practices, data was collected at the end of two workshops to validate the actual impact model from the engineering goals. The data from session one was collected and documented, and testimonial sessions were documented by the researcher from session two.

4.6.1 | Actual design support validation workshop 1 – written feedback based on questions below

Of 35 participants, 26 gave their response, a response rate of 74%. The questions were:

1. Do you now have a better understanding of the complexity and risks in the flow?
   a. If so, in which way?

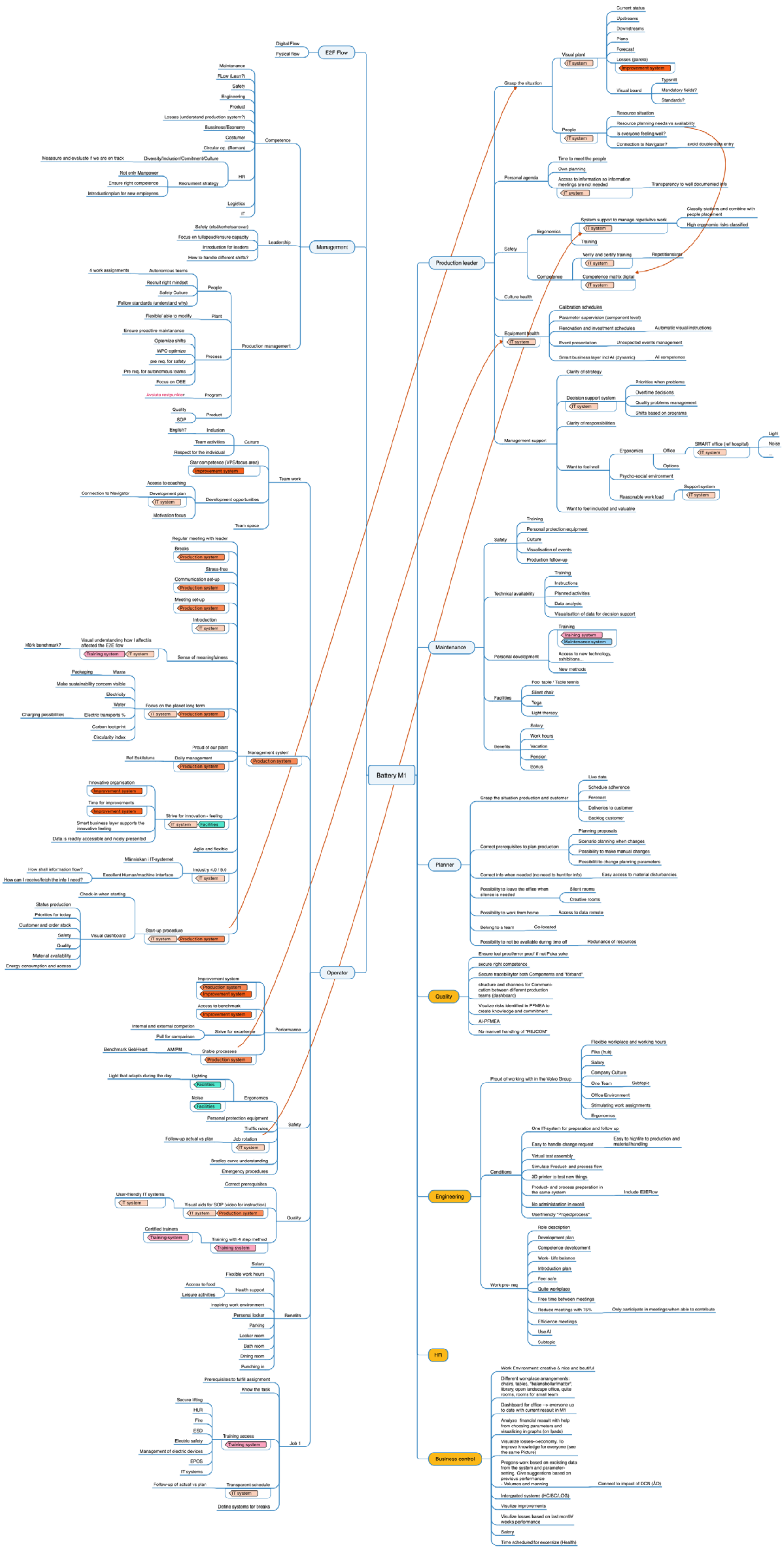

FIGURE 8 Model of the requirements identified in workshops, with the human in the system as the center.

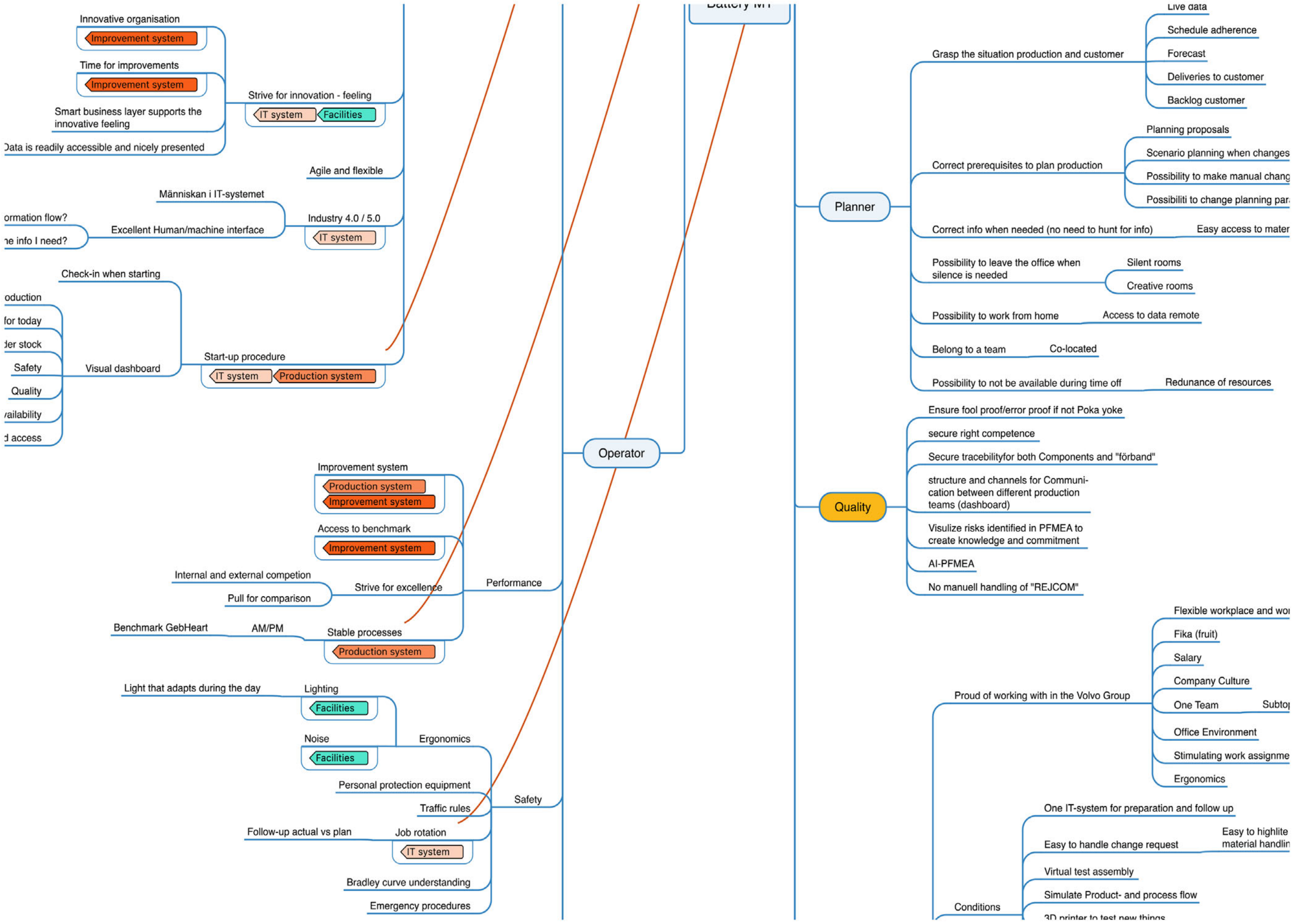

FIGURE 9 A zoom in on requirement model with tags per requirement or requirement family.

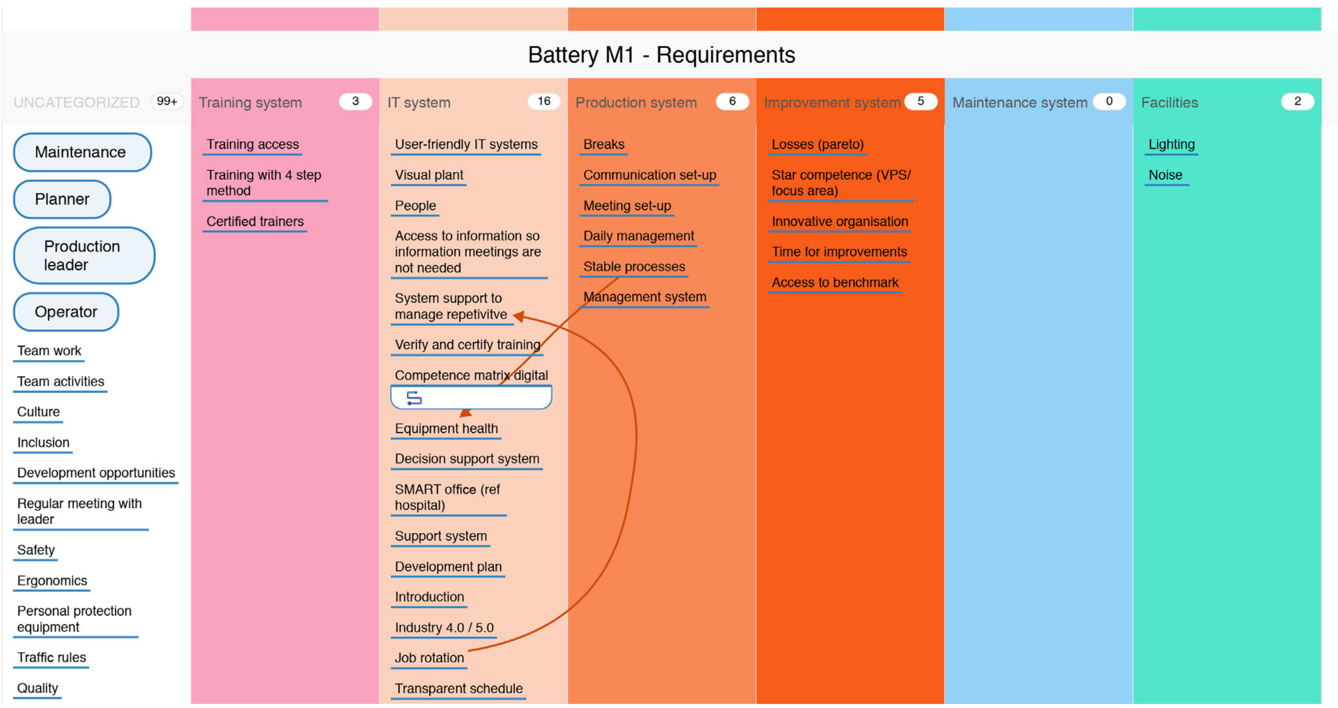

FIGURE 10 A zoom in on requirement model tag view per sub-system (in progress of being developed).

For question 1, all respondents stated Yes. For question a), several participants mentioned the overview and holistic view of the exercises with the combination of going down to documenting details: "I now have the overview of several processes, not just my own", "It is clearer now that we are considering all aspects, it is very easy to miss the details." "Great to listen to all perspectives and document every aspect." Several of the participants realized new things that they did not consider beforehand: "I realise how significant the logistics and planning will be," "I realise that there are still many things we do not know." The workshops also seemed to be considered energetic to the participants, supported by statements such as "Fun exercise with so many perspectives!", "Interesting to have the end-to-end perspectives."

4.6.2 | Actual design support validation workshop 2 – Testimonials on film

In this session, seven people were sharing their reflection on this way of working in general from different functions, hierarchical levels and backgrounds. One maintenance technician stated: "Really good input from the cross-functional teams. This helps us to get a wider perspective to see the bigger and end to end perspective." An engineering representative said: "Easy to get stuck in your own silos so this is a way for this big project to get the holistic view," and another engineer stated, "Very interesting concept, we have been very cross-functional and went in to the questions in a completely different way looking into the humans that should work in the environment." From the operators, who normally are not included as early as in this project, the feedback was "Great that we all meet and see our faces, so many different projects that need to be combined." Another aspect that can traditionally be included in later stages in industrial projects, the logistics organizations, said: "Good with the entire supply chain and end to end perspective, good to see all different areas and to learn from each other." This way of working is also new to the IT community who traditionally is organized within their own organization and not integrated with production. Statements from them were "It has been a number of workshops; it really invites people to participate in the journey. I can see so many people from different areas, a lot of input for us in IT to work on." IT also stated: "It has been very fun, a lot of learning from each other, coming together as one team."

4.7 | Summary of actual design support validation

From this exercise, 60 new demands from production to IT were identified and added to the work plan of the industrial project. For confidentiality reasons, these demands cannot be shared. The fulfilment by the actual design support to the engineering goals are described in Table 3.

The fulfilment by the actual design support to the intended impact model are described in Table 4.

4.8 | Summary of results

A summary of the results is described in Table 5.

5 | DISCUSSION

The findings from the study show promising results when it comes to address the engineering goals to manage risk, within the scope of component development of production management part of a battery assembly industrial plant project. The comprehensive prescriptive study approach was considered appropriate for this type of research. However, as the project is still on an abstract component level, the goals are not as precise and measurable as the theory of the research methods proposes. From this perspective, the generalizability can be more difficult to prove. On the other hand, design research is important also in very early stages of development where the concepts are still to be developed.

What is new in this project is that all the actors in the production system are invited from production, normally it is the engineering department that invited what is named as "stakeholders," where traditionally the human aspects have not been specifically highlighted as in this project, working with personas. Previously, personas have only been used from the central HR team. To work with and to emphasize the important of visual models to gain understanding from all actors is also something new for the organization. Still, one gap that was identified in the literature review was the insufficient commitment from functional departments. Their presence was increased in this project but still not up to expected levels,

The feedback and validations were surprisingly positive for the researchers. One aspect could be that the teams felt it was fun to be part of a research project and that they received a lot of attention, and also that the researchers are managers in the plant which could mean that participants felt pressure to reflect enthusiasm. Another unexpected finding was that the participants felt that this was such a new way of working. These concepts have been available for a long time but, as the literature review also states, it seems like they have not reached the engineering community within production system design. One aspect could be that the product design department of the company gets a lot of resources and are in numbers 10 times the resources in production system design, even though the investment levels into production systems are also large in scale. The reason why the product development is prioritized could be from bias from management; that the products in themselves is so much more important than the production system that should deliver these products at world class levels for perhaps 20 years.

Regarding managerial aspects, it is important to challenge the current ways of working and make sure the organization is up to date in methods and skills to deliver the future industrial systems, Industry 5.0. These systems should support not only a resilient production system over time but also within the planetary boundaries and embracing the full scope of a human-centric approach. This study was only a case

TABLE 3 Fulfilment by the actual design support to the engineering goals.

Engineering goal	Total	Yes	No	Confirming statement (selection)
Manage risk	26	26	–	☐ "It is clearer now that we are considering all aspects, it is very easy to miss the details." ☐ "Great to listen to all perspectives and document every aspect." ☐ "I realise how significant the logistics and planning will be." ☐ "I realise that there are still many things we do not know." ☐ "Really good input from the cross-functional teams. This helps us to get a wider perspective to see the bigger and end to end perspective." ☐ "Easy to get stuck in your own silos so this is a way for this big project to get the holistic view." ☐ "It has been a number of workshops; it really invites people to participate in the journey. I can see so many people from different areas, a lot of input for us in IT to work on."

TABLE 4 Fulfilment by the actual design support to intended impact model.

Intended impact model	Confirming statement (selection)
Transform cross-functional requirements to specifications	"Really good input from the cross-functional teams. This helps us to get a wider perspective to see the bigger and end to end perspective"
Define requirements from operators and production leaders to specifications	"Great that we all meet and see our faces, so many different projects that need to be combined"
Visual and user-friendly models explaining the source of specifications	"It is clearer now that we are considering all aspects, it is very easy to miss the details."
Using methods to connect and bring to life the humans in the system	"It has been a number of workshops; it really invites people to participate in the journey. I can see so many people from different areas, a lot of input for us in IT to work on"
Workshops where requirements are shared and documented	"Great to listen to all perspectives and document every aspect"

TABLE 5 Summary of research results for the comprehensive predictive study.

Topic	Sub-topics	Fulfilment
Task clarification	Results from earlier projects	Results from earlier projects had shown that the engineering focus was more equipment-oriented than production system-oriented
	Reference Model	Model-based engineering and Design Thinking
	Literature on similar goals	Described in the Frame of Reference
	Intended Impact Model	Intended Impact model described
Conceptualization	Functions of Intended Support	Intended Support Description is described
	Intended Introduction Plan	The concept was tested in the study in six workshops
Elaboration	Existing literature on Intended Support	Described in the Frame of Reference
	Intended Support fully described	The documentation and visualization of the models were to be performed by the researchers and experts
	Intended Impact Model finalized	Intended Impact model described
Realization	Core functionalities of Intended Support	Visual requirements model is used to get a shared picture in the entire organization of how the business will operate.
	Actual Support developed	Visual requirements model method developed with actual visual requirement model as example
	Actual Impact Model	Intended Impact Model fulfilled by Actual Impact Model
Support evaluation	Actual Support evaluated and modified if necessary	To confirm that visual requirements modeling was verified as relevant for engineering practices, data was collected at the end of two workshops and validated the Actual Impact Model from the Engineering Goals.

study to take the engineering community to using systematic, state-of-the art methods demands a lot from management and organizational ability to sustain.

6 | CONCLUSION

6.1 | Conclusion of RQ1

RQ1: How can visual requirements modelling be used to reduce risk in design of a new battery manufacturing system preparing for Industry 5.0?

The Design Support concept method to develop a visual requirement model was developed and delivered three artefacts on three levels of abstraction: the model of requirements from the human in the system, the categorization of system requirements, and the new 60 specifications towards IT. This approach addressed issues identified in literature complementing the existing methods with new perspectives, which encouraged creativity and cross-functionality. The approach supported the transfer of knowledge within and between development teams. The approach supported in building models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. This approach supported in including the humans in the systems already from the beginning, to address the issues that engineering often see the human aspects as an afterthought. By this approach, several aspects were identified that were not addressed and work groups were started to design solutions. However, the gaps of the effectiveness in the methods could not be evaluated yet as the project is still running for a few more years.

6.2 | Conclusion RQ2

RQ2: What can be learnt by using visual requirements modelling in design of a new battery manufacturing system preparing for Industry 5.0 to reduce complexity and risk?

From the interviews with the participants in the workshops, the main learnings are that everyone thought that using these methods is helping to manage risk. It was also appreciated to be more rigorous in the documentation than previous projects, as one focus of the workshops was to document the concepts selected and develop a system concept of the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Statements regarding the importance to get the overview that they were missing before, and the importance of cross-functionality and collaboration.

Recommendations for future work are to further explore what the production system design engineering community would harvest from the product development community, if these methods would have any actual impact on project cost and lead-time overruns, workload of engineers, and better production systems in terms of resilience, sustainability, and human factors.

DATA AVAILABILITY STATEMENT

Data is shared in the paper.

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