Department of Design

User involvement in safety-critical system design

Hanna Koskinen

Aalto University

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Abstract

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Abstract

Designing tools for performing safety-critical work tasks is demanding engineering discipline. Numerous highly specialized engineering knowledge needs to be integrated to create a well-functioning design solution that appropriately serves carrying out the work and fulfilling the goals of the activity. The design task of this magnitude goes easily beyond the capabilities of an individual designer. Consequently, representing a considerable collaboration challenge to the design process.

Expert users (e.g., process control operators) are a group of specialists that could potentially contribute much to developing the appropriate solutions. Many industrial standards also demand acknowledging the end user perspective in design. However, the expert users' role in the context of safety-critical design, have conventionally been restricted to involving the users in the later evaluation phases. At the same time, at these later stages, there may only be remote possibilities to make any radical changes to the design regarding the identified needs by the expert users. Yet, the tools are an integral part of the safety-critical system and the sensitivity that relates to the ability of expert users to operatively master their tools should not be forgotten. From the overall safety perspective, it is also highly relevant how the expert users know and use their tools. Therefore, this thesis aims to promote early expert user involvement in design of safety-critical systems and thus enable better inclusion of their hands-on experience and wealth of operative knowledge in design. The expert users should be involved in at the early stage of the design and the participation of the expert users should continue throughout the design process and the lifecycle of the system.

This thesis presents the development of method which facilitates participative processes and enables involving the expert users in safety-critical system design. The functional modeling of Tools-in-Use (TiU) is introduced in the thesis to facilitate constructive designer – user interaction and discussion about the different aspects of the emerging design solution. Within the TiU model both the functional content of work (i.e., the core task functions) and the design solution (regarding to its abstract concept as well as the concrete interface levels) are explicated. The TiU model provides, in a condensed form, a demonstration of how the different characteristics of the design solution may contribute to achieving the objectives of the activity. In addition, the TiU model emphasizes the meaning of understanding the work activity as a basis for forming the design rationale and aids reflecting the different design decisions against that rationale throughout the iterative maturation of the design solution.

The contribution this thesis makes is in the intersection of the research fields of human factors and ergonomics, human-centered design (including participatory processes) and usability engineering. The empirical work in this thesis has been conducted in several safety-critical work domains such as nuclear power process control and pesticide spraying activity in arable farming.

Keywords Human factors; design; safety-critical systems; expert user involvement

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Tiivistelmä

Turvallisuuskriittisten työtehtävien suorittamiseen tarvittavien järjestelmien ja työvälineiden suunnittelu on vaativa insinööritehtävä. Hyvin toimivan ja tarkoituksenmukaisen suunnitteluratkaisun luominen vaatii monenlaisen tekniikan- ja tieteenalan ammattilaisen erityisosaamisen yhdistämistä. Tällaisen kokonaisuuden rakentaminen on tehtävä, joka helposti ylittää yksittäisen suunnittelijan osaamisen rajat.

Turvallisuuskriittisten järjestelmien loppukäyttäjät (esim. prosessinohjaajat) voisivat omalla operatiivisella kokemuksellaan osallistua toimivien suunnitteluratkaisuiden määrittämiseen ja löytämiseen. Useat teollisuuden standardit myös edellyttävät käyttäjänäkökulman huomioimista suunnittelussa. Tästä huolimatta käyttäjien osallistuminen turvallisuuskriittisten järjestelmien suunnittelussa on perinteisesti rajoittunut lähinnä loppuvaiheen käyttäjätestaukseen. Samanaikaisesti tiedetään, että suunnittelun edettyä pitkälle, testauksessa mahdollisesti havaittuja käyttäjä- ja muutostarpeita voi olla vaikeaa ja kallista enää toteuttaa. Teknologiset työvälineet ovat oleellinen osa nykypäivän moderneja turvallisuuskriittisiä järjestelmiä ja se, miten hyvin käyttäjät hallitsevat ja ymmärtävät näiden työvälineiden käytön on ammatillisesti hyvin sensitiivistä ja sitä ei tulisi suunnittelussakaan jättää huomioimatta. Väitöskirjan keskeinen tavoite on edistää ammattikäyttäjien aikaista osallistamista turvallisuuskriittisten järjestelmien suunnitteluun niin, että heidän käytännönkokemuksensa ja runsas operatiivinen tietämyksensä tulisi hyödynnetyksi ratkaisuita kehittäessä. Käyttäjät tulisi osallistaa suunnitteluun alusta asti aina läpi koko suunnitteluprosessin ja järjestelmän elinkaaren.

Väitöskirjassa esitellään menetelmä, joka tukee osallistavan suunnitteluprosessin kehittymistä ja ammattikäyttäjien osallistumista turvallisuuskriittisten järjestelmien suunnitteluun. Funktionaalinen mallinnusmenetelmä 'Tools-in-Use' (TiU) esitellään keinona fasilitoida rakentavaa suunnittelija – käyttäjä vuorovaikutusta sekä keskustella kehitettävän suunnitteluratkaisun eri piirteistä. TiU mallin avulla sekä työ (perustehtävä) että suunnitteluratkaisu (abstrakti konsepti- ja konkreettinen käyttöliittymä taso) tulevat sisällöllisesti analysoiduksi ja käsitellyksi. TiU malli avulla voidaan tiivistetyssä muodossa tarkastella miten kehitettävän suunnitteluratkaisun eri osat myötävaikuttavat toiminnalle asetettujen tavoitteiden saavuttamisessa. Lisäksi TiU malli korostaa työn perustehtävän ymmärtämisen tärkeyttä suunnitteluperusteiden määrittämisen lähtökohtana sekä mahdollistaa yksittäisten suunnittelupäätösten peilaamisen tätä vasten.

Väitöskirjan kontribuutio sijoittuu human factors suunnittelun, käyttäjäkeskeisen suunnittelun sekä käytettävyys suunnittelun leikkauspisteeseen. Väitöskirjassa esitelty empiirinen työ sijoittuu erilaisiin turvallisuuskriittisiin toimintaympäristöihin kuten ydinvoimalan prosessinohjaukseen sekä kasvinsuojeluaineiden ruiskuttamiseen pellonviljelyssä.

Avainsanat Human factors; turvallisuuskriittiset järjestelmät; käyttäjien osallistaminen

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Acknowledgements

Thinking back in time, how I ended up working at VTT and on human factors issues, I must mention two initiatory change agents on my pathway. The first one being the fact that I really do not like a cold climate which in the first place made me to start looking for exchange opportunities locating more south than the Lapland University, Rovaniemi where I was studying industrial design. The second agent was a visiting lecturer who was teaching us a course at the university but who also was living in southern Finland where I am from. Few times we travelled together with the same Friday evening fight and thus had opportunities to have discussions. During one flight, we discussed about the potential exchange universities, and he suggested looking at the Delft University of Technology, a new exchange partner that the department had just made a contract with. I did not waste too much time before sending in my application after visiting their webpages and in the next autumn, I started my exchange year at Delft. Delft had a rich curriculum and I quickly learned of how much there were research on and to learn from different design methods, processes, and approaches. This was really an eye-opening experience and I realized that I would like to orient myself more towards a design engineering discipline instead of an art and graft-based design. The next summers, I was working as a trainee in product development departments in metal industry. I had the opportunity (but also the burden) to work as a first industrial designer in these companies and experience the everyday product development work, the design problems, and solutions, and sometimes also the design approaches that to me appeared unnecessary narrow and not integrative in a way that could have been possible when considering all the knowhow and professional skills of the people working there had. Surprise of all to me was how little the most obvious source of information about the products, that is, the users were considered in the design. These experiences from the practice led me to study and conduct the research which today is presented in this thesis. Even though I consider myself quite decisive and hands-on in realizing different projects, no words would have committed to this book without the support of many people that I now want to thank for.

No other person can I express more my gratitude than to my thesis advisor Research Professor, Docent Leena Norros. Before I joined her research team at VTT, I participated in her course on designing and developing sociotechnical systems at Helsinki University of Technology. The course was the very core I believed I would like to do in the future, and she introduced me with the relevant

tools (theories and methods) that I would need in this endeavor. I want to also thank you for inviting me to your team after the course and all the years that we have worked together. You always have a clear vision and ability to inspire developing oneself scientifically further.

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I have honoured to have Professor Pascal Béguin from the Université Lumiere Lyon 2 and Associate Professor Ole Broberg from the Technical University of Denmark as the preliminary examiners of my thesis. Your feedback and suggestions for improvements proved to be most helpful in finishing of the work. Furthermore, I am grateful and curiously looking forward also having Professor Pascal Béguin as the opponent in the puplic defence of my thesis.

The articles included in this thesis have been a result of a true collaboration and teamwork. I want to thank all my knowledgeable and inspiring co-authors who are many and include in addition to the already mentioned Leena Norros: Dr. Jari Laarni who I have had a pleasure working with from the beginning of my VTT career and who has in that spirit been co-authoring me in the first as well as the last of the listed articles in this thesis. I have learned a lot from you, and I have really enjoyed developing the research ideas and manuscripts together with you. Dr. Paula Savioja whose Systems usability construct has been central for our team's human factors methods development and who I had a pleasure to co-author in our Core Task Design book. I really appreciate the forward-looking attitude of yours and the critical questions that are always essential to develop the things forward. Other of my co-authors, Petri Honkamaa, Lars Hurlen, Susanna Aromaa, Vladimir Goriachev and Joakim Bergroth, I have always collaborated in research project at issue. I am grateful for the collaborative writing and working together on interesting topics. Yours comments and suggestions for improvements were critical in advancing the quality of each of the articles. I also want to express my gratitude to Liisa Pesonen, a fellow researcher from SmartAgriFood- project, as well as the other tens of anonymous reviewers that have provided valuable comments during the process of writing the articles included in this thesis.

The collaborative research work at our VTT human factors team have always been a great source of inspiration in developing the research ideas also presented in this thesis. In addition to the already mentioned persons, I want to thank my team leaders both the present team leader Mikael Wahlström and the former leaders Eija Kaasinen and Raimo Launonen as well as all the other members of our human factors team Marja Liinasuo, Tuisku-Tuuli Salonen, Hanna Lammi, Päivi Heikkilä, Antti Tammela, Bastian Tammentie and the former

team members Iina Aaltonen, Hannu Karvonen, Maiju Aikala, Tiina Kymäläinen, Antti Väätänen and Göran Granholm. Number of other persons outside of our core team also should be thanked for. First, I want to thank Technology Manager Jari Hämäläinen for believing and hiring me even though I had very different (art-based) educational background than most of the VTT researchers. In addition, in variety of interesting projects (and lunch breaks between them), I have had pleasure to work with many good VTT colleagues Kaupo Viitanen, Antti Pakonen, Jussi Lahtinen, Maaria Nuutinen, Marketta Niemelä, Teemu Tommila, Pirkko Rämä, Janne Valkonen, Tatu Harviainen, Antero Karvonen, Esko Lehtonen, Jutta Nyblom, Petteri Alahuhta, Markku Kivinen and many others.

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When being abroad having an international community around you is especially valuable which is why I want to mention and to thank my fellow researchers from OECD Halden reactor project Michael Hildebrandt, Pierrig Le Darz, John Kvalem, Ann Britt Skjerve, Mario Hoffman, Andreas Bye, Matias and Sirpa Ahonen, Giulio Gola, Steven Mullet, Hiroki and Ria Hanakawa, Nathan Lau, and Alexandre Lavoil. You made my visit both professionally and leisure-wise experience rich. In addition, during my stay at Halden we conducted empirical field work at one nuclear power plant at USA. I want to thank the experienced personnel from the plant's outage organisation that we had a possibility to interview. Furthermore, I want to thank Dr. Eva Simonsen from Vattenfall and Dr. Ronald Boring from Idaho National Laboratory from the many valuable discussions on the topic of developing the human perspective in control room system design.

The funding bodies must also be thanked. Most of the research was carried out within the Finnish National Research Programs on Nuclear Safety SAFIR. Within this research program, the research has also been funded by the OECD Halden Reactor Project (in which I also was working as a visiting researcher for 1 ½ years), Fortum Oyj, Teollisuuden Voima Oyj, and VTT. Additionally, I have received direct funding from VTT (working hours and printing cost) and Aalto University through Design department's Doctoral Candidate Position.

My family, friends and relatives have provided me a lot of support if not in scientific terms but more importantly as words of encouragement and interest. My mum Tiina and aunt Leena have provided childcare whenever needed and my father Sakari hours of construction work so that our other project, that is, the house renovation also has been able to move forward.

My brother asked me once; in what space of time, I have managed to do this thesis. Now when the project is coming to its end, I am wondering the same. The same pace as this thesis project has been extended also the number of my closest ones have been multiplied. Oscar, Ewald,, Selma, and Ines you are most important to me and I thank you for making also this professional journey in many ways more meaningful.

Westend, 23 January 2023
Hanna Koskinen

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List of Abbreviations and Symbols

ADDs	active design documents
AMC	acute medical coordination
AT	activity theory
ATM	air traffic management
CHAT	cultural-historical activity theory
CR	control room
DCs	design cards
DSS	decision support system
EPR	electronic patient record
FDA	Food and Drug Administration
HCD	human-centered design
HCI	human-computer interaction
HF / E	human factors and ergonomics
HSI	human-system interaction
HSIL	Human–System Interface Laboratory
ICU	intensive care unit
ISO	International Organization for Standardization
I2S-LWR	integral inherently safe light water reactor
NPP	nuclear power plant
OCC	onshore collaborative center
RQ	research question
SAFIR	Finnish Nuclear Safety research programme
SMR	small and modular reactor

SSW	software shaping workshop
SU	systems usability
UI	user interface
V&V	verification and validation

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

1. Koskinen, Hanna; Laarni, Jari; Honkamaa, Petri. 2008. Hands-on the process control: users' preferences and associations on hand movements. In: CHI '08 Human Factors in Computing Systems Extended Abstracts. Florence, Italy April 5-10. ACM. Doi. 10.1145/1358628.1358808.

2. Koskinen, Hanna; Hurlen, Lars. 2011. Outage on the table: the design of interactive surfaces for collaborative operation in outage control centres. In: ECCE '11 the European Conference on Cognitive Ergonomics. Rostock, Germany August 24-26. ACM. Doi 10.1145/2074712.2074725

3. Koskinen, Hanna. 2015. Book Chapter 4: Foreseeing: How to uncover the promise of solutions for future work. In Norros, L., Savioja, P., Koskinen, H. 2015. Core-Task Design. Synthesis Lectures on Human-Centered Informatics. Springer, Cham. https://doi.org/10.1007/978-3-031-02211-1_4

4. Koskinen, Hanna; Norros, Leena. 2018. The participatory design of tools: Foreseeing the potential of future internet enabled farming. Journal of Interaction Design and Architecture(s*)*. 37. 175-205.

5. Koskinen, Hanna; Laarni, Jari; Bergroth, Joakim. 2022. User Involvement in Design of a Safety-Critical Operating Panel System. International Journal of Industrial Ergonomics. 92, 2022, 103358. Elsevier. Doi. 10.1016/j.ergon.2022.103358.

6. Koskinen, Hanna; Aromaa, Susanna; Goriachev, Vladimir. 2021. Human Factors Engineering Program Development and User Involvement in Design of Automatic Tram. In the IADIS International Journal on Computer Science and Information Systems. 16 (2), 61-76. ISSN: 1646-3692

Author's Contribution

Publication 1: Hands-on the process control: users' preferences and associations on hand movements

Paper 1 presents results from an exploratory user study involving an interactive display system. The study was realized within a research project called Novel Affordances in Smart Environments (NASE). Koskinen had a major role in conducting the review of background literature (i.e., literature on hand movements and ergonomics) and forming the initial plan for the exploratory user study. The study plan was then collaboratively refined with Laarni. Honkamaa had the main responsibility for organizing the technical issues for the user study. Koskinen conducted the actual user tests and collected the data. The data analysis was done in collaboration between Koskinen and Laarni. Laarni did the statistical tests of the data and Koskinen analyzed the qualitative interview data and video recordings. Koskinen wrote the main content of the paper with feedback from Laarni and Honkamaa.

Publication 2: Outage on the table: the design of interactive surfaces for collaborative operation in outage control centres

Paper 2 presents results from a research project studying outage control center operation and specifically the use of interactive large screen displays during outages at nuclear power plants. Conducting the design and fieldwork within the research project was a collective effort of the authors. Koskinen wrote the main content of the manuscript and Hurlen participated in commenting on and revising the manuscript. Koskinen was the main author of the paper.

Publication 3: Foreseeing: How to uncover the promise of solutions for future work

Paper 3 is based on research work carried out in the Euratom-funded MMotion project and in particular the research efforts realized in the Work Package 3 feasibility study and pilot exercise. Norros and Koskinen proposed an evaluation method that was selected to be piloted within the work package. Norros and Koskinen were the main persons responsible for planning the evaluation. The evaluation was carried out as an international collaboration effort on the FITNESS simulator platform at the SEPTEN Électricité de France (EDF) site in Villeurbanne (France). The data analysis and reporting of the results of the evaluation in the form of a Deliverable (Results of the Pilot Exercise) was conducted in collaboration with the work package participants. Koskinen wrote

the book chapter based on the pilot exercise with feedback from the co-authors of the book, Norros and Savioja.

Publication 4: The participatory design of tools: Foreseeing the potential of future internet enabled farming

Paper 4 describes the user involvement activities in a research project focusing on future Internet-enabled smart farming and food production. Conducting the user studies and analyzing the data was a collective effort of the authors and other international partners in the Smart Farming and User Community and Dissemination work packages in the project. Koskinen wrote the main content of the manuscript based on the research work in the project. Norros participated in writing and commenting on the manuscript. Koskinen is the main author of the paper.

Publication 5: User Involvement in Design of a Safety-Critical Operating Panel System

Paper 5 presents results from several research projects related to the design of human-system interfaces for the main control room of a nuclear power plant. All the reported research studies were carried out in human factors projects under the Finnish Nuclear Safety research programme (SAFIR). Koskinen has been in a central role in planning, conducting, and analyzing the user studies that were conducted as a collaborative effort of the researchers working on the projects. Koskinen planned and wrote the main content of the manuscript, and Laarni participated in writing and commenting on all parts of the paper. Bergroth as an industry representative was the person responsible for the technical simulator setup for the reported studies in the paper, and he commented on details describing the used technologies in the manuscript. Koskinen was the main author of the paper.

Publication 6: Human Factors Engineering Program Development and User Involvement in Design of Automatic Tram

Paper 6 describes the results of a VTT self-funded research project, and the work carried out under the verification and validation process for an autonomous systems task, in which Koskinen was one of the responsible researchers. The other two authors of the paper, Aromaa and Goriachev, worked on a different task, namely the development of a VR simulator environment for the automatic tram, which was introduced in the paper as one means of involving users. Koskinen planned and wrote the main content of the manuscript with feedback from the co-authors, Aromaa and Goriachev.

1. Introduction

In our everyday lives, we use a variety of artifacts and tools to achieve our ambitions. The modern world affords us new digital opportunities and ways to connect with each other and our surroundings. Digitalization and new advanced technologies are a reality in the context of modern industrial work as well. Expert users (e.g., human operators with extensive professional training and usage experience) responsible for handling critical tasks and controlling safety-critical industrial processes are introduced to new digital technologies aiming at enhancing the productivity and safety of systems. This inevitable trend will profoundly affect not only the functioning of the system as a whole, but also the everyday work practices of the expert users.

Process control operators, for example, often have an extensive professional background and experience in the use of several generations of tools in their work. For example, over the course of their careers, they might have experienced the transition from paper-based procedures to the use of computer-based procedures. This operational history and knowledge about different tools is also an asset when human operators adopt new work practices and the use of new digital tools. However, the sensitivity that relates to the ability of expert users and professionals to operatively master the use of their tools should not be forgotten. That is to say, the operators are the best experts in their field (i.e., operation of the system) and they have the most hands-on experience and formal training on how to use specific tools to carry out their daily operative tasks. Furthermore, what is meant with "a tool" in this thesis is understood broadly; that is, a tool is the mediating technological element of the socio-technical system. For example, in the process-control context, the whole control room environment together with all the operating procedures and communication equipment may be seen as a comprehensive tool of the operators.

From the point of view of the overall safety of the system, it is highly relevant how the expert users know and master their tools. For that reason, the design and development of safety-critical systems should be sensitive to the opinions and concerns of those who will ultimately be the main users of the new tools and who are expected to work daily to run the systems in an efficient and safe manner. Thus, if the human operators have a role to play in the operation of the systems, their experience and understanding of the meaning of the new tools and their potential impacts on operation should be viewed as important and be carefully considered in the design and development of these systems.

Nuclear process control operators represent one specific group of expert users whose involvement in the design of safety-critical systems is sought. They are the individuals who will eventually use the system on a day-to-day basis and who ultimately assess whether the new design meets the set requirements. These expert users are experts at the tasks that they perform, and they may have undergone an extensive training program before being allowed to become a fully authorized member of an operating team. Therefore, it is clear that these expert users possess a wealth of knowledge that may provide an important source of information in design.

The research presented in this thesis has been carried out in the human factors team at VTT Technical Research Centre of Finland Ltd. My 15-year-long career as a research scientist in this team sets the larger organizational context in which the research work included in this thesis has been carried out.

VTT is a technical research organization that does research on a variety of important societal challenges and issues such as the internet, climate change and renewable materials, to mention but a few. Today, VTT has around 2,000 researchers working on both national and international projects in the public and private sectors. VTT's multidisciplinary human factors team is focused on studying the roles of humans and their activities in industrial and work environments. Over the years, the human factors team has conducted research on a number of work contexts (e.g., in the process industry, machinery and rescue operations) as well as carried out methodical development (Norros et al., 2015) on design and evaluations of work systems. One central domain in which the team has advanced its methodological base for human factors studies is the nuclear field; the Finnish national nuclear safety programme (SAFIR) has provided a natural framework for this.

As a part of my work at VTT, I was also committed as a visiting researcher (i.e., a secondee) for a period of one and a half years at the OECD Halden Reactor Project hosted by the Institute for Energy Technology (IFE), which provided me with a more international view and connections to human factors in the nuclear domain. Overall, at VTT I have had the possibility to work closely with the industry and engage in solving practical human factors problems that always have timely relevance.

Particularly, my contribution in the VTT human factors teams, and within this thesis is on contributing methods that facilitate and enable participatory processes to take place, allowing expert users to engage in the design of their future work practices and tools. Safety-critical systems such as nuclear power plant (NPP) main control room (CR) environments are the empirical context in which the studies within this thesis are carried out. Safety-critical systems may be defined as those systems whose failure could, in the worst-case scenario, cause loss of life or significant damage to the property or the surrounding environment (Knight, 2002). Well-known examples of safety-critical systems and work environments include different medical facilities and devices (e.g., intensive care

units), aircraft flight and air-traffic control systems as well as a variety of industrial installations like NPPs. [1]

1.1 Motivation of the study

The research presented in this thesis is motivated by the significant changes that the digital transformation and ever-increasing use of automation solutions and other advanced technologies may cause in the design and operation of safety-critical systems. For example, conventional hardwired analog interface technology based NPP control rooms undergo extensive modifications when the automation systems are modernized (Nystad et al., 2011). The work of surgeons will also change when advanced robot surgery solutions are deployed in operating theaters (Aaltonen & Wahlström, 2018).

Design decisions made and solutions created in the design phase of the system life cycle have an important bearing on the overall safety of systems. In fact, it has been reported that half of the root causes of accidents in safety-critical domains (including aviation, railway, and nuclear industries) lie in design (Kinnersley & Roelen, 2007). Moreover, when looking at all the statistically recorded accidents and incidents due to human and organizational factors, the numbers of cases are even higher. That is why, for example, after several serious incidents and accidents in the nuclear field, regulatory bodies worldwide have set recommendations and stricter standards that include human factors and ergonomics considerations in the design of NPP control systems. The assumption is that acknowledging human issues appropriately in the design phase is one crucial way to improve safety. For example, according to the nuclear-specific NUREG 0711 (USNRC, 2012) review document, several elements need to be in place so that human factors and ergonomic issues may be appropriately integrated into design. These elements are operational experience review, reference system analysis, functional requirement and functional allocation analysis, task analysis, human-centered design (HCD), operating procedure development, personnel training, and verification & validation (V&V) process. All these analyses may produce important information for the design, while HCD (ISO-13407, 1999) provides principles and a process for the inclusion of human and social aspects throughout the design.

When thinking about all the elements mentioned in the NUREG 0711 review document referred to above, it is not hard to imagine how expert users could contribute to them with their knowledge and understanding. Due to their contextual/operational experience, expert users may be in a particularly good position to estimate how the proposed new design solutions affect and enable aspects such as resilience (Hollnagel et al, 2011) in the system. Human operators' capability to adapt to changing situations and flexibly draw on their earlier experiences (e.g., to handle an accident situation appropriately) is a great source of resilience and one reason why expert users still play a role in the concept of

[1] With respect to safety-critical systems, the military domain is the only sector that is excluded from the scope of this dissertation; examples of numerous critical operation environments in other sectors are discussed.

operation in safety-critical systems today. Similarly, in design, it is not possible to anticipate all the future occurrences and happenings beforehand, but expert users with their operational experience may provide a valuable contribution by reflecting on the use of the new solution in different operational situations. This provides yet another reason why the expert users' opinions and understanding should not be dismissed in design.

There are several studies pointing out the importance of user involvement in the design and development of human-system interfaces (HSIs) (Damodaran, 2017; Kujala, 2003; Wilson & Haines, 1997). For example, eliciting concrete feedback by involving users in design may yield a more accurate set of user requirements or make it possible to avoid costly and undesired system features later when the system has already been implemented and is in the operative stage. Involving expert users may also improve general system understanding and thus help operate the system safely and more efficiently. According to Saleem (Saleem, 1996), the benefits from user involvement become even more evident and vital for system acceptance in a situation where users have greater system-related functional expertise that overpowers the other members of the design team. That is why, in the design of safety-critical systems, the expert users (e.g., process control operators) with extensive domain-specific training and operating background may play an important role in defining the system characteristics and setting the requirements. For example, in the NPP CR design context, operators have been successfully involved in designing the concept of operation for the use of large screen displays in main CR (Laarni et al., 2008). In this study, the CR operators participated in defining the physical setup for the displays, the ways of managing and operating them, and the content (i.e., process and other information) that should be displayed on the screens. While the importance and potential benefits of expert-user knowledge in design seem to be widely recognized, many studies point out that in practice involving users and achieving clear benefits through this in design is anything but straightforward (Balfour et al., 2012; Money et al., 2011).

Even though one of the driving principles of HCD is the active involvement of users, the guidance on how to initiate and carry out participatory activities in practice and throughout the design is somewhat general. One possible source of problems in the context of safety-critical system design is that the users are quite distant from the design; they may not be familiar with the design process or the many constraints on the design and realization of certain solutions. Moreover, the technical aspects of the design, which in many ways are more concrete to handle and may impede the whole design process if not solved early on, often overpower the expert users' opinions and concerns about critical design decisions. It may also be that the expert users are involved in and asked for their opinions when all the critical design decisions have already been made and the impact of the users' opinions remains minimal. In the case of ever-changing and larger contexts such as hospital districts or industrial clusters (e.g., shipbuilding industry), designers and developers may have difficulties in finding and making contact with relevant user groups. Furthermore, it has also been reported that designers lack methodological knowledge on how to involve expert users and

further process the acquired user feedback so that it can be used meaningfully in design (Balfour et al., 2012). So, to this day, there are still many unresolved methodological issues in involving expert users in safety-critical system design and carrying out HCD including participatory processes in a systematic and mature way throughout the design process.

Therefore, the research in this thesis is motivated by the aim of fully capitalizing on the potential value of involving expert users in design and enabling them to participate in the design of their future work practices and tools. That is to say, the motivation is to promote the professional user experience and knowledge in design. Therefore, the research in this thesis is motivated by the aim of fully capitalizing on the potential value of involving expert users in design and enabling them to participate in the design of their future work practices and tools. That is to say, the motivation is to promote the professional user experience and knowledge in design.

1.2 Research object and goals

This thesis concerns the integration of expert users' knowledge and experiences into the design and development of safety-critical systems such as CR environments. Thus, the object of research is the participatory processes in safety-critical system design and the particular goal is to methodologically contribute to *user involvement in the design of tools for safety-critical work*.

As stated above, user involvement may be especially beneficial when the users are expected to have far superior contextual expertise and knowledge than the other members of the design team (Saleem, 1996). That is why in the design of safety-critical systems in which expert users often (e.g., process control operators) possess high professional skills and domain knowledge, user involvement can be especially advantageous. The expert users may better comprehend how the new proposed tools affect their work. They may also have certain professional reflective/anticipatory capabilities to estimate how promising (i.e., good, and purposeful) the new tool is early on in the design process if the concept is mediated to them in some illustrative way.

Designing and developing safety-critical work systems is also a complex and highly networked activity. Integration of various disciplines is required to respond to design challenges such as the increasing complexity of systems, continuous change and ever-higher efficiency and quality demands. Within an integrated design process, diverse design disciplines and tasks may communicate, collaborate, and coordinate their activities effectively (Papin, 2002). Human factors engineering (HFE) is a design discipline that has a long tradition in the context of the development of safety-critical systems. It also provides a wider perspective for user involvement, as through the HFE process human and social aspects become considered and organized in system design. Thus, the design organization – and especially HFE – has a central role in defining the value of expert user knowledge and enabling user involvement through its processes. For example, some companies largely outsource their design, which naturally af-

fects contact surfaces and collaboration between the use and design organizations. The HFE process generally – and how it methodologically supports user participation in solving practical problems in complex work – is essential from the point of view of developing more systematic and holistic user involvement procedures.

As defined above, the research object is the safety-critical system design, and the main goal is to contribute methodologically to user involvement in the design of tools for safety-critical work. However, in order to treat the user involvement in a contextually meaningful way, it is necessary to also pay attention to and study its boundary domains to some extent – that is to say, to look into 1) the general HFE organization and activities (e.g., HCD process) within which the user participation is intended to be arranged, and 2) the characteristics of complex work activity and the content of profound expert knowledge/understanding that may contribute to the design. Figure 1 illustrates the boundary domains that are essential for investigating and developing research methods enabling expert user participation in safety-critical system design.

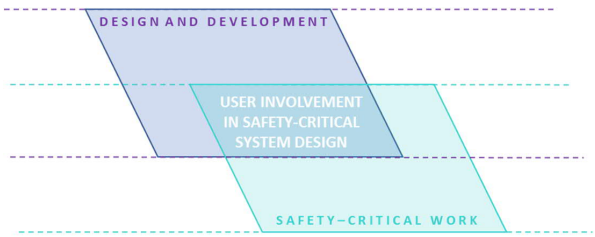

Figure 1. The boundary domains (design and operation) of expert user involvement in the design of complex safety-critical systems.

1.3 Conceptual basis of the study

Many relevant scientific fields of research have influenced the work presented in this thesis. Below I introduce the main ideas and concepts used in the relevant fields of research.

1.3.1 Theoretical background

The American psychologist James J. Gibson (Gibson, 1979) coined the term "affordance" in the 1970s. It was a key concept in his ecological psychology theory of visual perception. "Affordance" refers to the complementarity and interaction between an organism (e.g., human actor) and an ambient environment. Gibson used affordance to describe those things that an environment furnishes with an animal through interaction. For instance, if an object has a flat, rigid, level, and extended surface, and if the proportions are well suited to the human observer, it is probably safe to sit on (that is, it has the affordance of "being able to sit on"). Thus, these separate properties of an environment are combined to yield a higher order property, such as in the above example the property of sitability. According to Gibson, an affordance is easier to perceive than isolated

properties of the environment; he states, “the invariant combination of properties is meaningful whereas any single property is not.” (Gibson, 1979)

The mutuality that characterizes the relationship between actors and their surroundings is a key feature and fundamental idea in the ecological approach. For that very same reason, the affordance concept has been of wide interest to researchers working in the field of human-computer (system) interaction (Hartson, 2003; Kaptelinin et al., 2012; Norman, 1999). For example, Kim Vicente (Vicente, 1999) has noted that the mainstream viewpoint in psychology, human factors and HCI has been based on a cognitive perspective that focuses on understanding the constraints that the human cognitive system imposes on goal-directed behavior. The ecological approach to design, however, gives precedence to the constraints that the work ecology imposes on goal-directed behavior (K. J. Vicente, 1999; K. J. Vicente & Rasmussen, 1990). According to Rasmussen (Rasmussen & Pejtersen, 1995) one common problem with contemporary interfaces is that they tend to be designed bottom-up, as represented by the typical single sensor, single indicator type of display (creating an abundance of data). While using this kind of display, the user needs to integrate all of the information it presents in order to build up a mental picture of the status of the system in relation to the achievement of its overall goal (Wong et al., 1997).

The ecological approach suggests that work design should begin with an explicit analysis of the constraints that the environment imposes on action; then, in the design of displays, the information should be organized to portray the relationship and structure between the states of physical components, the functions they serve, and the goals the system is intended to achieve. Enabling direct perception in an interface design led to a situation where the user can readily make assessments of how changes to the states of the components affect the achievement of the goals, and how changes in goals or the external environment need to be responded to (Wong et al., 1997). The ecological approach to design and especially the concept of affordance has in many ways been influential to VTT’s human factors team as well as my research work from the beginning of my career as a part of that team – and consequently to the research work presented in this thesis.

The human factors and ergonomics (HF/E) discipline, which originates from the Anglo-American tradition, represents an important field of research to this thesis. HF/E is defined as a “scientific discipline concerned with the understanding of interactions among human and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance”(ISO_9241-210, 2010). Thus, the aim of human factors with a specific focus on the interaction between the human and other elements of the system is to improve overall productivity, safety, and comfort in using the system. Under the umbrella of HF/E, there are hundreds of methods and specific scientific approaches (Stanton et al., 2005). The methods are important in HF/E, as they provide human factors professionals (or ergonomists) with a structured way of analyzing and evaluating design problems. In the nuclear field, human factors and ergonomics work has a long tradition and the HF/E research is carried out comprehensively

from a variety of perspectives such as physical, cognitive, and organizational ergonomics points of view. In the selection of methods as well as the use and analysis of collected data in the NPP context, methods that allow making interpretations in an objective way are traditionally favored. This often leads to the use of methods based on conducting controlled experiments that provide results in the form of quantitative data.

However, the use of these types of quantitative methods has also caused some challenges. For example, as the sample sizes of operators that can be recruited for HF/E experiments are often notably small, it is difficult to reach adequate statistical power. Moreover, it may not be possible to compare datasets and carry out benchmarking so easily, as the control rooms are more or less unique entities. In addition, it has been found that transforming the quantitative data into design recommendations and implications is not that straightforward either, and thus a more qualitative understanding of control room activity and the meaning of the outcome of the evaluations and HF experiments are needed to complement and explain the findings (Norros, 2014).

The cultural-historical activity theory (CHAT) or the activity theory (AT) (Leont'ev, 1978; Vygotsky, 1978) and the ecological approach to human-environment interaction have provided an important theoretical background to the research work carried out in human factors team at VTT. Moreover, a cognitive system engineering (CSE) approach with its unit of analysis – that is, a cognitive system and the central aim of analyzing how human agents cope with and master the complexity of processes and technological environments and how the control within the system can be improved – have been influential to the views of VTT's research team on human-system interaction (Hollnagel & Woods, 1983; Roth et al., n.d.; Woods & Roth, 1988).

In doing research on human-system interaction and developing work practices and tools in a variety of industrial contexts at VTT, the human factors team has also needed to take a stance on and follow the developments in related fields such as Human-Computer Interaction (HCI) and usability engineering (Nielsen, 1993) as well as the research carried out by communities like Computer Supported Collaborative Work (CSCW) and CHI: Conference on Human Factors in Computing Systems. The basic aim and emphasis of Human-Centered Design (HCD) and User-Centered Design (UCD) – to use ergonomic methods to collect human performance data, so that the allocation of user needs, and their preferences are considered in all phases of design – is compatible with VTT's human factors team's and my intention to be proactive and have an impact on designing successful and user valued design outcomes.

1.3.2 Frame of reference for the study

Drawing from the scientific approaches and theoretical underpinnings described above, core-task analysis (CTA) (Norros, 2004) was developed in VTT's human factors team to describe the central content of the work and characterization of the users' expertise. Core-task analysis draws on the notion of function, that is, "a goal-relevant structural property of a work domain. Affordance that is relevant to the purposes for which the work domain was designed" (Vicente,

1999). CTA involves modeling these functions and analyzing the requirements that the fulfillment of the functions imposes on the activity in the work domain. This yields an understanding of the so-called core tasks (i.e., tasks that need to be always maintained in that specific work activity).

The core task is a kind of more generic and functional description of the work, and it may serve as a natural reference for the design of new solutions and development of work, and thus provides an important framework to this thesis. In analyzing the core task, discussions with expert users and an understanding of the work context are prerequisites; however, to facilitate more active expert users' participation in design it become necessary to develop the use of the core-task concept to be more design-oriented and to allow the expert users with their wealth of expertise to influence the design decisions more directly.

The concept of systems usability (SU) (Savioja, 2014b) that was developed to evaluate the systemic effects of a tool is another grounding concept for the research work of VTT's human factors team. SU is a human-centered quality attribute of tools, but the value of the tools for the activity that they aim to serve is evidenced by the successful performance of the activity at large. Consequently, SU as an evaluation frame addresses the significance of individual technological solutions in, and for, the entire activity system. SU is central from the point of view of evaluating the overall functioning of the system and it describes the sought-for good quality of the tools. In this thesis, the SU concept is utilized in the elicitation of the knowledge and experiences of the expert users who are expected to contribute and be critical in designing systems with high SU.

In the case of designing industrial CRs, dozens of technical disciplines and engineering knowledge have to be integrated in order to create a well-functioning whole. In this connection, it is a challenge to facilitate foreseeing bigger development paths and making innovation leaps (Wahlström et al., 2016) instead of just focusing on incremental improvements or generating solutions for carrying out individual tasks and operations. To solve this problem VTT human factors team developed a further conception of CTA. VTT's human factors team, including my specific designer contribution, developed a Core Task Design (CTD) (Norros et al., 2015) concept. The aim of this extended concept is to allow formative design interventions and a better integration of an appropriate human factors point of view in the design of safety-critical systems. CTD extends the unit of analysis from the analysis of the existing activity to the design of new activity and introduces a design model (see Norros et al., 2015) with three main functions: 1) understand to generalize, 2) foresee the promise and 3) intervene to develop. CTD has thus already been shifting the general focus of VTT's human factors team to a more design-oriented direction.

The main contribution of the research work presented in this thesis is to continue developing the concept of Core Task Design, and particularly the contribution is to facilitate participatory processes and expert user involvement, and thereby to strengthen the second function of the design model, that is, foresee the promise of the new activity.

As a specific contribution of this thesis, the Tools-in-Use (TiU) modeling approach is proposed as a methodological aid to connect the proposed design solution to the generalized main content of the work activity (i.e., core task), thereby allowing contextualized reflections to be made on the value of the new solution. The consequence of concentrating only on task- and situation-specific solutions is that it is difficult to master the task-artifact cycle (i.e., the activity sets requirements for the designed technology and, when implemented and used, the new design produces a shift in the activity itself). Consequently, developing the work with long-term overall goals in mind becomes difficult. Therefore, the foundational principle of the research work in this thesis is to always seek to facilitate viewing the proposed design solutions (however small or radical those are) also from the perspective of the overall work activity and not just the individual moment of interaction or task execution point of view. The great belief is that when the expert users are truly involved in the design and they are helped to discover the different characteristics of the emerging design solution from the overall work perspective, they can see opportunities and development paths that no other design party may see.

1.4 Research questions

Main research question:

How can participatory methods for expert user reflection on work – including both exploring and evaluating individual task demands and future development prospects – be furthered to better integrate human and social considerations in safety-critical system design?

The above main research question is related to finding methodological ways to enable expert users to explore their work activity broadly and attend to design by engaging in professional reflection on the potential of new tool designs. The method should capitalize on the broad and deep competence that the experts have in terms of knowledge, skills, and experiences through practice and training in a particular field of safety-critical operation. This expertise enables the users to make reflections that are not limited solely to a singular solution or operative situation but are instead more universal and conceptual in nature, that is to say, concern the future directions/prospects of the work activity. Thus, the methods used to involve expert users in design should draw from the full capabilities of these professional operators.

Sub-question 1:

What kinds of participatory practices are currently taking place in safety-critical human- system interaction design?

Sub-question 2:

What kinds of functional models of work should be used as methodological means to facilitate expert-user reflection on work and as a presentation around which constructive discussion between the designers and users can take place early on in the design process?

Sub-question 3:

What kinds of contributions can expert users deliver for safety-critical systems design in different phases of the product lifecycle?

1.5 Research approach and method

My designer background has equipped me with a certain pragmatic stance on research work in safety-critical system design. I believe that using a combination of methods (originating from and representing a variety of different scientific disciplines) enables creating a richer picture that acknowledges a multitude of perspectives concerning the design task and complexities of the problems (Jamieson, 2007). Each design task is unique and thus investigating it appropriately may require the utilization of a number of methods. Consequently, using multiple points of view to investigate the task at hand may result in a more profound understanding of the problem space, deeper description of the design rationale and findings with stronger explanatory power. Therefore, the research work carried out in this thesis applies a mixed model approach and draws on several scientific research disciplines – of which the most important are described above in Section 1.3 – for inspiration to advance expert user involvement.

The motivation of this thesis, that is, fully capitalizing on the potential value of involving expert users in design already strongly orientates the selected research approach toward the discipline of design engineering and design research. Designers – including industrial designers such as the author of this thesis ¬– have been trained to approach the object of design through an iterative development process in which the solution is sequentially refined to reach an appropriate outcome. The development process of an artifact may start from only a very vague idea or from a more mature and tangible product, but all the same it is developed further to respond to the need to make an impact in its context of use. Thus, the user needs and preferences (i.e., in-depth knowledge about the unique and specific problem at hand) have always comprised one of the central focus areas of designers' work.

The studies included in this thesis have had varying starting points. One project was sparked by an idea about the use of a specific technology in a particular use context to allow more tangible and natural interaction in the era of digital displays. In another project, the HSI concept had already been developed further, challenging the conventional presentation formats for industrial process control even though it was still in the concept design phase and under user testing. These design tasks have been generally approached here from a pragmatic viewpoint (Creswell, 2014). Consequently, the most suitable-seeming process and methods are utilized to solve the design tasks at hand without letting any philosophical underpinning restrict the thinking too much. It is accepted that different approaches and points of view can complement each other and thus contribute to solving the problem.

Design sciences provide many relevant views that can be considered influential for the research work in this thesis. Design sciences are concerned with de-

veloping knowledge, tools, and techniques to create desirable and usable artifacts. Consequently, better understanding how expert users could be involved in design so as to be able to advance the general human factors' methodical toolkit in designing safety-critical systems may be this thesis contribution regarding to the design science. Like the type of design research called research for design (Frayling, 1993), this thesis is to improve and develop design practice – and in particular to advance the collaborative and participatory processes required to reach integrated design solutions. The outcome of research for design can take the form of design methods, recommendations, and implications as well as more general frameworks or design philosophies.

One methodical question that comes across repeatedly is what kind of model or representation could capture the developing design solutions in a way that would support the shared understanding of the design team and potentially also speak to expert users who often may not have any technical design background. The present thesis does not aim to make an all-embracing and detailed (technically valid) model of the design solution, but instead something usable in safety-critical system design practice that allows constructive discussion to take place, and which is also feasible in design practice in other ways such as resource use (expertise and time needed) and documenting. Thus, the research work in this dissertation is very much what is in the focus of research for design (i.e., improve the design practices) (Norros, 2014).

Another influential approach is research through design (Frayling, 1993; Zimmerman et al., 2007) according to which new knowledge can be generated mainly by building and exploring prototypes (i.e., understanding the complex situation, framing, and reframing it and based on that understanding iteratively developing the prototypes that address the situation). In the context of the design of safety-critical systems, the expert users are the ultimate owners of the problem. One potential benefit of involving expert users in design by applying principles of research through design could therefore be that the focus on the context of use could be deepened/elaborated even further.

Through the generative process of transforming ideas into concepts and prototypes, the designers need to balance between the opportunities and constraints and adjust them in line with the realities of the world. This analysis - development process in itself may produce new insights that may be relevant from the research point of view and be shared with others, which is one of the carrying ideas of research through design. When considering the aim of this thesis the, that is, the expert user involvement in safety-critical system design, the notion of research through design provides methodical inspiration as well as some kind of ideal of what the participatory processes could be about, that is, mutual learning of future prospects through collaborative design activities.

1.5.1 Research method

The methodical framework applied in this thesis builds on the core task analysis that has provided a basis for the development of a practice-theory approach to human factors, that is, the core-task design (CTD) concept (Norros et al.,

2015). In CTD, the work is considered to be a practice that is composed of human actors, the physical and social environment, and the tools used in the work to reach its objectives. Thus, according to CTD, human factors should adopt practice as a new unit of analysis and perceive that interventions (in opposition to the objective approach) are an inherent feature of developing the systems.

Generally, in CTD, three design functions are introduced and central to maintain in design: 1) understand-to-generalize, 2) foresee-the-promise and 3) intervene-to-develop (see Figure 2, Norros et al., 2015). Within the first function (i.e., understand-to-generalize), an empirical analysis of the work is carried out in order to comprehend the general control demands of that specific work activity, that is, to conceptualize the core activity. The second function (i.e., foresee-the-promise) is dedicated to creating concepts for future work, that is, to define the potential activity. The third function (i.e., intervene-to-develop) aims at participatory development and design of work, that is, to create the new actual activity. However, CTD should not be understood as a description of the sequential design process/ methodical steps but as three functions that are valid and present in design simultaneously, yet with a varying emphasis at different times and phases of the design process. The CTD design functions enable viewing the activity from three distinct perspectives. Changing the perspective can be seen as responsible for the creative power of CTD.

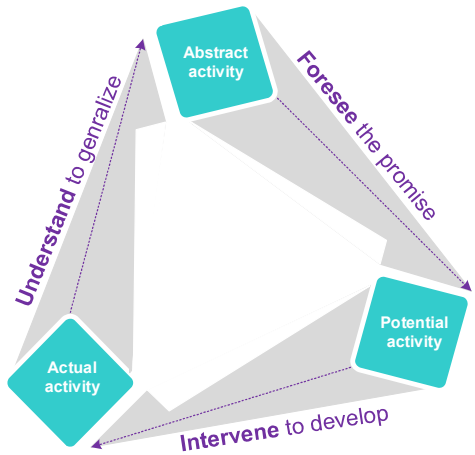

Figure 2. The Core-Task Design model, with three design functions that enable the transformation of the object of design from concrete into abstract activity (core), then potential activity, and the emerging new actual activity (figure adapted from Norros et al., 2015).

A collection of human factors methods is introduced within CTD to benefit the three design functions. Consequently, analyzing the core-task (CTA) and later CTD as a comprehensive design approach have provided a starting point and methodical framework within which the research work and studies included in this thesis have been carried out.

CTD can be seen representing the tradition of a functional thinking in design and one central methodical idea is the transition in different levels of abstraction (i.e., moving from concrete to abstract and vice versa). These methodical underpinnings have greatly influenced and build-in also the way how the expert user involvement and designer – user interaction is approached and methodically structured in the research work presented in this thesis. Within the CDT framework this thesis and answering the research questions aim to specially support methodically the foresee-the-promise design function that mediates transferring between the core activity (a kind of abstract generalization of present activity) and potential activity (a kind of abstract projection of future activity).

1.5.2 Progress of the study

The research work presented in this thesis has progressed following a process similar to many research projects (see Figure 3). First, a relevant research topic has been identified, then the related literature has been evaluated from which gaps in existing research have been identified that has aid in setting the final research questions. Then the initial TiU model was developed as an answer to the question of how to involve expert users in design and development of their work and tools. The potential of TiU model was tested in different research projects and contexts which enabled making assessment of its usefulness and finally answering the research questions.

Each of the empirical case studies included in this thesis was a part of a different research project (see the lower part in Figure 3). The research projects had varying research goals and organizations, and thus varied in terms of how they proceeded in their details. However, the overall process often followed similar iterative steps in which initial analysis was followed by some empirical field studies and, finally, the project evaluation phase in which the appropriateness of the outcomes was assessed. The human factors work in these research projects was also organized according to this iterative research and development process.

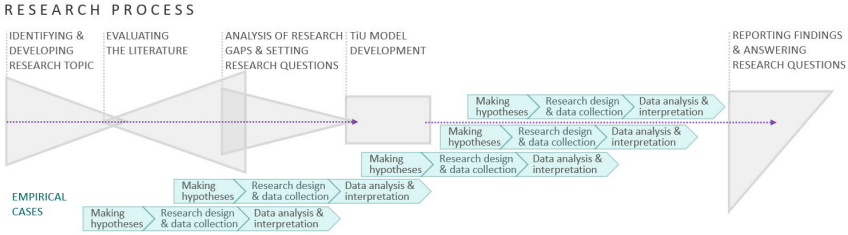

Figure 3. Illustration of the proceeding of the research process in the research work presented in the thesis

The development of expert user involvement in safety-critical system design has followed much the same iterative process. First, the TiU model that has been used as a basis for interacting with the expert user has been developed and built. Then, the TiU model has been used in a variety of design activities involving

number of expert users, after which its functioning and usefulness have been reflected on to enable the further development of the model as a participatory design method.

The studies included in this thesis have provided possibilities to build and develop methods for involving expert users in design as well as testing and evaluating the methodologies in real design cases. In a way similar to how initial design ideas emerge and assume more sophisticated forms as prototypes and products, the method for involving expert users in safety-critical system design presented in this thesis has been developed over the years and during these studies. The research work carried out in these studies has provided possibilities to test and evaluate the method in different use contexts, in different phases of the design process and with a number of different user groups that have helped to both reflect on the functioning and the usefulness of the method and develop it further.

1.6 Structure of the thesis

The rest of this thesis is structured as follows. The introductory Chapter 1 (including motivation of the study, research objects and goals, conceptual basis of the study, research questions, and research approach and method) is followed by Chapter 2, which reviews relevant research with the aim of identifying the methodological needs that create the foundation for further development and the contribution of this thesis to safety-critical system design. Chapter 3 summarizes the empirical studies carried out within this thesis. The main results achieved in this thesis are presented in Chapter 4. Following that, in Chapter 5, the meaning and contribution of the main results regarding user involvement and advancement of participatory processes in the context of safety-critical system design are discussed and concluded.

2. Related research

In this chapter, related research relevant for this thesis is reviewed and discussed.

Research concerning human-centered design within the human factors engineering process of system design, methods of participatory design and user involvement in safety-critical system design and subjective experiences of expert users in safety-critical work were explored in the process of identifying and developing the specific research topic of the thesis. around the research work was

aimed to be focused were –. This exploration was used to elaborate and develop the object and goals of the research work and generally guide the mapping of relevant research.

As discussed earlier, designing, and developing safety-critical systems such as CR systems is a complex and highly networked activity that requires cooperation between various kinds of disciplines. Thus, it is necessary to take a broader perspective and focus on human factors engineering that is a design discipline and has a long tradition in the context of the development of complex safety-critical systems. The particular emphasis of HFE in safety-critical system design is to analyze and recognize social and organizational complexity within the target system and guarantee that appropriate attention is given to human and social aspects in the design and operation of the system. For that reason, HFE also provides a wider context for expert user involvement, as the human and social aspects are considered and organized in the system design through the HFE process. To involve expert users in the design of safety-critical systems, it is important to understand how this participatory activity fits and may be integrated and contribute to the overall system design process. An extensive list of activities may be identified as main tasks within HFE related to CR and HSI systems. Generally, HFE includes the management and planning of a variety of HFE activities and processes (EPRI, 2004; ETSON European Technical Safety Organisations Network, 2013; USNRC, 2012). Among the other tasks of HFE, one central responsibility is to support and produce design-relevant information by applying knowledge about human capabilities and limitations to the system design. One approach to include human view in design is to follow the human-centered design philosophy and actively involve relevant user groups throughout the design and lifecycle of the target system (G. A. Boy, 2012; dos Santos et al., 2011; Farias et al., 2009; Kirwan et al., 1997). Nureg's HFE review model (USNRC, 2012) guides the involvement of plant personnel to ensure that the user's perspective is appropriately considered. Within the review of related research, a general understanding of the variety of approaches, staging and content of HFE activities within the safety-critical system lifecycle was inquired. Furthermore, it explores what the context of safety-critical system design means for developing and incorporating methods for involving expert users in design and how HCD is currently applied within the HFE work carried out in complex safety-critical system design.

The safety-critical system context is expected to have methodological implications for involving users in design. Thus, related research explores participatory design methods in safety-critical system design. The review focus is on concrete product development and design practices – that is, the level at which the designers and users may interact and collaboratively explore the design space to achieve a design solution of a high quality. However, there are countless design approaches and methods; here, the particular interest is in participatory design methods that enable expert users to be involved in the design of their own work practices and tools. Human-centered design places a central focus on user needs and the context of use in system development (ISO_9241-210, 2010). Further-

more, it emphasizes the meaning of active user involvement throughout the design process to create a design basis for user and task understanding. The benefits of human-centeredness and involving users in design are widely acknowledged and agreed upon, even though their cost-effectiveness has proven to be difficult to calculate (Bruseberg, 2008; Kujala, 2003). It has been also recognized that documents or second-hand information sources may not yield a deep enough understanding of the context of use; instead, it is essential to have direct contact with the relevant user group that may serve as a valuable source of information, feedback, and insights into design. Therefore, the methods that would early in the design process enable expert users to participate in exploring their work demands from a more comprehensive and overall safety point of view, instead of just contributing to the improvement of individual task sequences or processes are especially interesting. In addition, methods used in the context of safety-critical, high-complexity system design are reviewed in terms of their potential (i.e., benefits and challenges) to support design.

The subjective experiences and feelings of expert users in their work, also referred to as the concept of user experience (UX) is also essential when discussed about expert user involvement. Utilizing UX in the design of tools is based on the idea that the feelings and emotions of the user indicate the status of an activity as a whole (Kaptelinin, V., & Nardi, 2012). This user's subjective views may provide an important aspect, that is, an experiential dimension to safety-critical system design and facilitate gaining a deeper understanding of the essence of the complex work activity and the meaning of tools. In addition, contributions of users' knowledge and experiences may help in setting the relevant objectives for the design (ISO_11064-4, 2013; Jamieson, 2007) and provide a reference against which the new design solutions may be evaluated (O'Hara et al., 2012a). Although UX being somewhat vague concept some shared conceptual perspectives on UX have emerged (e.g., emphasis on holism and subjectivity). An international standard exists that defines UX as "a person's perceptions and responses that result from the use or anticipated use of a product, system or service"(ISO_9241-210, 2010). In this thesis, the concept of UX may not be the main focus, but as it may provide background on how complex work and tools are currently experienced in safety-critical system operation and how the users see their profession and work on its future development, it is relevant and aimed to be explored within review. UX is also one of the perspectives on activity in the systems usability (SU) (Savioja, 2014b) construct that VTT's human factors team has developed for systematic evaluation of complex systems. It is urged to gain a better understanding of the expert users' world, that is, the problems, challenges, and achievements they come across in their work. It is expected that UX may have implications and provide an important aspect when considering expert user involvement in the context of safety-critical system design.

2.1 Identification and description of the reviewed research literature

The related research was reviewed systematic way. The particular time period from which the scientific literature and studies was identified is the past 15 years (from 2006 to 2021). In addition, selected older studies and research examples were included if they were identified as relevant for the focus of the review. The literature search was executed with the following search strategy: First, a keyword-based search on specified databases was conducted. Secondly, reference chaining from the articles that were found relevant in the first phase (i.e., keyword-based search) was executed. Finally, focused searches on specific conferences such as Participatory Design were carried out, also going back 15 years in time.

In the keyword-based search, domain-specific terminology was looked at first and the final search words were adjusted accordingly. The final search words were: 1) participatory design, 2) participatory ergonomics, 3) safety-critical systems and end users, and 4) collaborative design. The review data were sought from EBSCOhost databases. Altogether, 16 450 articles and scientific papers were identified in the keyword-based search after which the titles of the articles were scanned through to identify the domain and the targeted activity. Of these articles, 195 documents were relevant and 52 met content and quality criteria related to expert user involvement in safety-critical system design. The 195 documents were additionally reviewed regarding their abstracts and conclusions, and the 52 that were identified highly relevant were most thoroughly reviewed. After that a reference chaining was executed by selecting from the reference lists those journal articles and conference papers that fell within the boundaries of the specified literature search criteria. After reviewing and verifying their relevance (by scanning of abstract and conclusions), a final decision concerning their inclusion or exclusion was made. In case of inclusion, the articles identified through reference chaining procedure were reviewed with the same precision than the 52 articles in the first phase. The criteria for including a paper as relevant was that the paper reported on a practical product-level development project in a safety-critical system context and had its focus on involving expert users in the design. Particularly, the literature search sought for papers reporting on their practical methods and tools of user involvement to varying degrees.

In the last phase of the literature search, a focused review on specific scientific conferences was carried out. These reviewed conferences had been recognized as being central in the earlier phases of the literature search, as the content of the papers included in their proceedings was often discussed and cited in the identified journal articles and studies. The reviewed conferences were Participatory Design Conference and Conference on Human Factors in Computing Systems.

An Excel sheet was prepared from the articles identified relevant. Each article was reviewed regarding following items; Publication details (year, author, title, journal, abstract), Study details (study type/aim, country, user/conduct of research, setting/context/key characteristics, target population/number of participants/sampling how recruited, characteristics of participants, detail of any

theory/ conceptual models), Nature of study (study date/duration, methods of data collection/ user participation, theory framework used to develop the user intervention, analysis method used), Results (outcome measures, detailed findings, strengths and limitations of the study, authors' conclusions). In addition, in the Excel own column was reserved the reviewer's own notes and summary of the relevance of the paper. Summarizing the content of the articles in above described matrix enabled both comprehending the overall status of research on expert user involvement in the safety-critical design as well as making more detailed comparisons, for example, related to the use of some specific participatory method.

While arguably not complete, the identified list to the best of my knowledge comprises the most important scientific arenas and journal issues relating to participatory design and user involvement.

2.2 Structure of reporting the results of the related research

Reporting of the reviewed research is divided into four subsections that are organized as follows: In subsection 2.3 Characteristics of safety-critical systems as objects of design, I review studies that concern characterizations of safety-critical systems as an object of design and the HFE process.

In subsection 2.4 Human-centered design of safety-critical systems, I review research that reports on the application of human-centered design practices in the development of safety-critical systems. The focus is on the design of the tools that the human operators use for handling and controlling the object of their work activity: for example, the design of CRs and the related HSIs in the case of process control work in the NPP context. Especially, I focus on the human-centered design activities and practices applied in the early phase of development. The review covers broadly studies and examples of related research from a wide range of safety-critical domains, but the emphasis is on the nuclear context, as it is the original interest and application area of my studies and most often the focus of the empirical studies represented in this thesis. My main motivation for looking into these practices is that human-centered design is reported to be followed in industry practice and it is also a requirement in a variety of standards (ISO 9241-210, 2009; USNRC, 2012) concerning the development of interactive systems. For example, in the NUREG 0711 (USNRC, 2012) standard, the requirements for the integration of ergonomics and human factors issues in nuclear equipment design are stated to include the following elements: operational experience review, reference system analysis, functional requirement analysis, functions allocation, task analysis, human-centered design, procedure development, training, and the verification and validation (V&V) process. The human-centered design approach emphasizes the use of human factors methods to collect human performance data for use in nuclear equipment and HSI development. However, what is actually meant with human-centered design is often not specified, not to mention what main methods and concrete design tools and techniques are utilized in following the human-centered design approach. This

is especially the case when talking about development at the product level instead of the inclusion of human and social issues at more general organizational and process levels (e.g., launching a HFE program). Thus, human-centered design is an extremely broad and somewhat vague concept. In the review, I concentrate on finding out how the human-centered design approach is actually applied in the design and development of safety-critical systems.

Subsection 2.5 User involvement in the design of safety-critical systems concentrates on reviewing the empirical studies on *participatory design practices, methods and tools* within the development of *safety-critical systems*. In pursuit of active user involvement in design, the enabling tools and methods are the main object of this thesis. However, few practical examples are reported in detail in the literature and most often the knowledge and practical user work remain hidden away inside the design organizations. In addition, the operational definitions of participative processes and user involvement may have been generally imprecise and, in many cases, the level of user involvement may have been greatly dependent on the interest of individuals working in the organizations. Therefore, there is a need to understand how user-related knowledge and user involvement are managed in organizations, and what design tools or techniques can be used to facilitate this process. Again, the primary domain in which the research and studies are reviewed is the nuclear domain, but other relevant industry sectors are also included. Other relevant domains are, for example, specialized medical workplaces such as operating theaters and intensive care units or air traffic control in the aviation context. Being open to experiences outside the nuclear domain is important because, as already mentioned above, it is expected that only a limited number of studies and practical examples on the topic can be found from the nuclear field. The motivation is to find ways of integrating the expertise and professional knowledge of users into the design so that the allocation of user needs and wishes in all phases of design can be guaranteed. In the review, I especially concentrated on finding answers to the questions: how should designer-user interaction be organized and how can the joint exploration of work practices be facilitated so that the collaboration results in design-relevant information (e.g., design specifications)?

In the fourth and synthesizing subsection 2.6 Discussion on methods for user involvement in safety-critical system design, I will summarize the insights and findings from the related research.

2.3 Characteristics of safety-critical systems as objects of design

2.3.1 Safety considerations are given first priority

Having a safety-critical system as an object of design without a doubt differs from the design of any other interactive system. Although designing may always aim at improvements to the current situation and system (e.g., regarding functionality or productivity), in the context of safety-critical systems, safety always remains the main concern. An accident in safety-critical system operation could harm not only individual workers but also the surrounding environment and

society. For example, in the context of air traffic control (ATC), Mackay (Mackay, 2000) notes that controllers hold the fates of thousands of people in their hands, and thus there is no room for any mistakes that could cause crashes. Generally, as Noyes et al (Noyes et al., 2017) states, in the avionics environment there are high costs associated with users interacting with poorly designed HSIs, as this could ultimately place the whole aircraft and its occupants at risk. Moreover, accidents in sectors such as nuclear power operation or the oil industry may also have extensive impacts on the surrounding environment and its vitality (e.g., the 2002 breakage and sinking of the tanker Prestige on the north coast of Spain caused substantial oil spillage; see discussion from the human factors point of view, e.g., (Chauvin, 2011).

Thus, in the design of safety-critical system operations, all characteristics and aspects of the working environment need to be carefully considered in setting the requirements for the system. A holistic approach is commonly advocated in the context of safety-critical system design. For example, in the nuclear context, dos Santos (dos Santos et al., 2008) defines five specific aspects of a system and their interrelations that may need to be taken into account in holistic analysis: namely, (1) the technological artifact being designed, (2) the user, (3) the various anticipated tasks, (4) the organization within which the technological artifact is used for carrying out different tasks and (5) the possible operational situations during the system's lifecycle. Hettinger et al (Hettinger et al., 2015), however, claim that it may be difficult to comprehend modern sociotechnical systems due to their high number of interconnected elements and subsystems. They argue that in many cases the overlooked or unintended consequences of changes to these kinds of complex systems are a frequent cause of safety risks and overall system malfunctions. Thus, they propose using advanced modeling and simulation techniques to study the system behavior and reach a proper understanding of the functioning of the sociotechnical systems to make informed design decisions that support safety.

2.3.2 Increasing complexity challenging the system design

The above already aptly illustrates the *complexity* involved in the design task of safety-critical systems. This complexity of the design task will increase even further as the systems themselves are expected to become increasingly complex in the future for various reasons. For example, in the maritime and air traffic management sectors, future growth in traffic may considerably add to the risks and challenges that the systems face (G. A. Boy, 2009; Hjelseth et al., 2015; Mackay, 2000). Mackay (Mackay, 2000), for instance, gives an illustrative example about the relationship between increasing air traffic and safety considerations in designing a new air traffic management (ATM) system. She describes the design task as being both ethical and political due to the rapidly growing volume of traffic and the state of the current system, which is in many ways extremely safe although not completely. Thus, according to her there are two optional paths to move on: first, the level of safety in the current system needs to be further improved, or second, growth in the amount of flights needs to be considerably restricted. The latter option, however, may have significant economic

consequences, which is why according to her, it is necessary to study how the efficiency/productivity of the current system could be improved without neglecting safety. Safety is the main concern of flight controllers; that said, they also care about efficient aircraft traffic, which is why they are under constant pressure as the complexity of the system grows.

One critical design question is how this complexity may be embodied in such a way that the human operators/users can still assess it. It may also be difficult to gain experiences and do testing in design on the influences of the growing complexity of the system. Hettinger et al. (Hettinger et al., 2015) describe the challenges that contemporary sociotechnical systems pose for designers to envision, study or even comprehend the different properties and characteristic of the system. Thus, they say that designers have to face high levels of uncertainty about the consequences of their design decisions, as it may be difficult to comprehend and understand their potential impact beforehand. The ever-larger size of these systems, which can have several thousands of interconnected variables, also poses challenges (G. A. Boy, 2012), as the users need to supervise and comprehend a growing number of parameters and connections and in the case of an adverse event know how to react appropriately in the specific situation at hand while still acknowledging the functioning of the whole. This requires a deep understanding of the system behavior. The same challenge applies in developing these interconnected sociotechnical systems (Hettinger et al., 2015), that is, it cannot be precisely predicted what effect the modification of an individual system element will cause on the other parts of the system.

Another issue related to the increase of complexity is that rapid advancements in technology and in particular in automation systems, have resulted in increasingly complicated and varied human-system interfaces. This, alongside the fact that the operational lifecycles of safety-critical systems are often relatively long, has led to one regular complaint by the users: Systems are not designed in an integrated manner, which means that over the years, the amount of different systems and interfaces that users need to interact with has increased to an almost unbearable level. Moreover, these systems may have different graphical presentation formats and interaction styles that further complicate operations, as for example, Bjørneseth (Bjørneseth et al., 2012) has noted happened in the context of ship bridge operation. Increasing levels of automation may also add further complexity, as the human operators who traditionally have been fully responsible for all operations now need to share operative responsibility with the automation system. Therefore, one critical design question within safety-critical systems is how to keep the human operator in the loop and maintain their feeling of control. For example, Boy (G. A. Boy, 2009) mentions that authority sharing is one of the major themes in developing future air traffic management systems and flight deck automation, given the fact that air traffic capacity will continue to increase, and it is necessary to find ways to improve efficiency by means of new automation solutions.

In recent years, the emergence of advanced technologies such as artificial intelligence (AI) based solutions has also been discussed. For example,

Gyldenkærne et al. (Gyldenkaerne et al., 2020) described how AI-based solutions in the healthcare context hold a fundamental promise, as AI can harness tremendous amounts of data (e.g., that is stored in existing electronic patient records) and in doing so potentially provides valuable insights. However, as they note, realizing this has not been straightforward. This is because in the design of AI-based systems, the data set is important, and the original data recording in most cases has not been specified with this purpose of use in mind, thus limiting the insights that the AI can elicit. According to Bratteteig and Verne (Bratteteig & Verne, 2018), advanced technologies like AI pose new challenges to design and maybe especially to participatory design activities since the current approach to AI is such that the computer deduces its "rules" from its experience with processing data (i.e., learning from the data through sophisticated statistical analyses). Potential users of these AI-based systems may have difficulties understanding what the system can or cannot do and consequently have difficulties in participating in the design decisions. Another challenging aspect of AI from the participatory design perspective, according to Bratteteig and Verne (Bratteteig & Verne, 2018), is that the AI component develops and changes over time, and thus evaluating the usefulness of the design solution requires a longitudinal testing period. Even if the user in principle understands the basic functioning of the AI, it is not possible to foresee fully how it will potentially develop and change the functioning of the system over time. Use of advanced and complex technologies surely challenges current human-centered design methods.

2.3.3 Standardization and regulations of system design

Another characteristic aspect of safety-critical systems as an object of design is that they are most often highly regulated domains. Thus, the possible design solutions need to comply with a number of standards, guidelines and safety regulations. Moreover, it is not only the end result of design that needs to fulfill these regulations – often the design and development process as well as the operation of the system are also strictly regulated and monitored by the authorities. The nuclear field represents one of the most regulated domains and the number of safety standards and guidelines has kept increasing since the early years of nuclear energy production. NUREG-0711 (USNRC, 2012), Human Factors Engineering Program Review Model provides one central guideline that the licensees' HFE activities need to be in compliance with. Other guidance exists also, for example, NUREG/CR-6396 (USNRC, 1997) Integrated System Validation: Methodology and Review Criteria and ISO 9241-210 (ISO_9241-210, 2010) Human Centered Design for Interactive Systems.

Many reports and scientific publications discuss the challenges and organization of the licensing process of new or modernized NPP control room projects (Boring et al., 2015a; Giaccardi, 2005). Traditionally, the prior focus of licensing has tended to be on late-stage activities, that is, the final summative evaluation or integrated system validation of CR and its design. In recent years, however, more attention has been given to developing guidance and methods for early

evaluations and, for example, knowledge elicitation, which is aimed to capture operator insights into the system design (Boring, Ulrich, Lew, et al., 2021).

In the context of designing offshore and gas installations, design is also subject to several standards. For example, in Norway, the Working Environment Act (The Norwegian Labour Inspection Authority (Arbeidstilsynet), 2017) obligates companies operating within the gas and oil sector to enable their employees to participate in decision-making concerning their workplace design and management (Balfour et al., 2012). The Norwegian petroleum and safety authority follows this and demands and states accordingly in its Framework Regulations (Norwegian Petroleum Safety Authority, n.d.). It is stated that the employees and their representatives are to be given an opportunity to contribute to matters that affect their working environment and safety of operation. This specific regulation comes already close to the topic of this dissertation. However, these regulations do not provide detailed guidance on how the employees' participation should be arranged and what kinds of methods and techniques could best support involving users in design. Thus, it remains a design challenge and the responsibility of the operating organization.

2.3.4 Constant change in systems

Generally, as in many other fields of life, the organizations responsible for operating safety-critical systems are currently going through *radical changes* (Andersen & Broberg, 2015; J. Simonsen & Hertzum, 2008). There are many reasons behind this, one of which is the abovementioned rapid technological advancements. Moreover, in many fields, much of the existing technological equipment is dated and obsolete; when trying to replace old and broken equipment, spare parts might no longer be manufactured and could be impossible to purchase. This problem is recognized widely, for example, in the nuclear and air traffic management contexts (R. Boring et al., 2015; Mackay, 2000). Consequently, one design challenge is balancing between the need for change and stability, that is, how radically the system should be renewed. For example, would it be possible to replace only part of the system with new technological solutions or does the whole system have to be fully modernized? Both cases present further practical design issues regarding, for example, scheduling and organizing the design work while at the same time keeping the system operative and safe.

Another trend that causes pressure to make radical changes and reorganize the operation within safety-critical systems is the trend of centralization. In many fields, efforts are made to improve efficiency and productivity by merging many smaller units to form one big "super" unit, or by at least handling the supervision and operation of the smaller units from one central operating center. The first of these seems to already be a reality in the healthcare sector, where the trend has been to build large hospital units that are often also highly specialized (J. Simonsen & Hertzum, 2012a). Examples of the latter alternative are, for example, the remote operation of container handling cranes in large ports (Koskinen et al., 2012) or, in the nuclear field, operating multiple small and modular reactors (SMRs) (O'Hara et al., 2012b) from one central control room. These kinds of triggers for change and new concepts of operation may present

very new kinds of challenges and human and social issues to be considered in the design of safety-critical systems.

2.3.5 Relevant user groups

Another characteristic issue, especially for designing safety-critical hospital operations, is the *expansion of the potential user groups*. At the same time as the size of the hospital units grows, so does the group of specialists needed to design and run their operations. According to Simonsen and Hertzum (J. Simonsen & Hertzum, 2012a), this leads to large numbers of varied user requirements that the design solution needs to acknowledge. In the intensive care unit (ICU) context, this large group of specialists and wide knowledge base needed for operations is well concretized. In the study of Björgvinsson (Björgvinsson, 2008), it was stated that various ICU patient categories require a very large knowledge base and the involvement of 140 medical specialists to run a 10-patient unit. Acknowledging all the needs and requirements of these diverse professionals, not to mention the patients and their families' perspectives, is a considerable design challenge. Moreover, Björgvinsson (Björgvinsson, 2008) notes that there is constant turnover in ICU stuff, which further complicates the identification of user needs and design requirements. Similar issues are found in the pre-hospital context (e.g., ambulance personnel and firefighters), that is, gaining the user perspective is challenging when the operations cut across "regional boundaries" and many levels of organizations, marked by the functional diversity of the user groups (Mogensen & Wollsen, 2014). Another issue that according to Garde (Garde & van der Voort, 2010) may hinder involving relevant users in design is that for medical specialists the patient care always comes first, and it may be difficult to organize time for innovative activities.

Overall, development projects (e.g., design and implementation of new patient record systems) in a hospital context are often large in scale and require the involvement of a great number of different actors representing different organizations and organization levels. Thus, the user roles are becoming increasingly unclear (Johannessen & Ellingsen, 2008). The challenge is that people have different experiences, needs and even professional languages that may hinder discussing the current practices as well as developing a shared vision of the future system and its operation. However, when looking at other kinds of safety-critical systems, the user populations may be characterized in almost the opposite terms. For example, in contexts such as nuclear power process control and operation of oil and gas installations, the group of users is often much smaller, at least in cases where one specific plant or oil platform is being renewed. Here, one key design challenge seems to be the low level of availability of expert users that may participate in designing the future systems due to their busy work schedules and the fact that the number of operators in these contexts is often much lower (Balfour et al., 2012; Zamberlan et al., 2012) than, for example, the number of professionals needed for running one ICU department. Balfour (Balfour et al., 2012) also points out that even access to offshore facilities may be very limited and relatively costly due to strict safety policies and the necessity of

helicopter and boat transportation. Thus, it may be difficult to build long-term relationships and involvement of these experts in the design process.

2.3.6 Systems are often one of a kind

The design and evaluation of safety-critical systems are often challenged by the fact that the constructed systems are unique by their nature. This means that experiences from other similar design projects and requirements elicitation methods such as benchmarking may not produce information that is precise enough to be directly applicable in the design of a new system. However, for example, Noyes et al. (Noyes et al., 2017) have emphasized the importance of consulting an expert flight-deck crew (i.e., the users of the current system) in the design of a new aircraft warning system. According to them, the rationale is to elicit the preferences and requirements of experts to enable the identification of the strengths and weaknesses in the HSIs of the current system. In the design of a new system, those attributes that were considered to be favorable could then be enhanced while avoiding or improving upon less desirable features. However, the authors admit that eliciting a relevant set of design guidelines from user knowledge is not a straightforward process and remains a methodological design challenge.

From the evaluation point of view, defining a baseline and acceptance criteria for the system's usability and safety justification may also be more difficult when there is no similar system with which the results could be compared. Thus, in designing safety-critical systems, integration of knowledge from various disciplines is needed and a complex network of different actors produces the final system/design solution. Managing this type of development process logistically and schedule-wise is a huge design challenge. For example, in the shipbuilding industry, the different stakeholders are often scattered both geographically and organizationally, and due to this and the various backgrounds of the design parties, it may be difficult to find a common language and carry out collaborative design. Not all seafarers may be able to read technical drawings and comment on them, and not all highly specialized design engineers are able to understand and emphasize the problems and challenges faced in everyday ship operation. With respect to designing in a hospital context, Garde and van der Voort (Garde & van der Voort, 2010) point out that one critical factor for successful outcomes in operating theaters is the communication between the hospital and the system vendors. Similarly, Johannessen at al. (Johannessen & Ellingsen, 2008) suggest that the traditionally neutral vendor role should be critically examined so that the real user needs and wishes could be met in the design process.

Finally, one design issue that causes frustration and challenges is the length of the design processes of safety-critical systems. It is characteristic of these development projects that they can take many years or even decades to complete (ETSON European Technical Safety Organisations Network, 2013; Rajala & Väyrynen, 2011). For example, in the context of modernizing NPP control room systems, it is not uncommon for one project to take as long as 5 to 10 years in total. Managing the information flow in such design processes calls for system-

atic documentation and accumulation of design evidence and knowledge (Kinnersley & Roelen, 2007). In the hospital and healthcare context, however, it seems that the tempo of the agile software development process common to companies that deliver IT systems to this sector causes its own kinds of problems with respect to acknowledging expert users' perspective (Money et al., 2011). It may be that the vendor's design process considers the customer as having a single voice as a user, when in fact the end users in the hospital context represent many user groups. Moreover, it may be difficult to elicit relevant user requirements and feedback within the agile development cycles (e.g., which may be as short as three weeks).

2.4 Human-centered design of safety-critical systems

In the following subsection, I present studies and research in which the application of human-centered design practices in the context of safety-critical systems is discussed and investigated. The motivation is to find out how human-centered design is perceived by organizations that run safety-critical operations, such as air traffic management operation and electric power generation. In their view, what kind of value does the human-centered design approach bring to the design of safety-critical systems? What kinds of practical methods do they use to implement human-centeredness in their development processes? ISO 11064-4 (ISO_11064-4, 2013) specifies the procedure for the ergonomic design of industrial control rooms. Among the main design principles, that is, error tolerant design, feedback design approach and use of task analysis methods identified by this standard, it recommends the application of a human-centered design approach (ISO 9241-210, 2009) in the development of control centers.

Development of human factors engineering practice and acknowledging the human aspect in the design of safety-critical systems has often led to advancements through accidents that have forced the operating community to focus attention on problems in organizational arrangements or human-system interaction. For example, in the nuclear domain, the accident at Three Mile Island was a turning point that concretized that the human aspect can no longer be ignored in control room and HSI design. In the maritime industry, and especially in vessel bridge operation, it has been estimated that human related issues are the cause of 80% of accidents (Shea & Grady, 1998); despite this, Bjørneseth et al. (Bjørneseth et al., 2012) argue that human factors are still rarely considered in vessel design and engineering to this day. That is why it is essential to try to understand not only the challenges and obstacles that may hinder the use of human-centered methods, but also the benefits that are gained through efforts put into better inclusion of humans and organizational factors in design. Human-centered design and a focus on users aim at producing user-friendly design solutions that are well rooted in the practices of the people using these solutions (i.e., equipment and tools) in their work. According to dos Santos et al. (dos Santos et al., 2011) human factors studies are essential in ensuring that the primary objectives of improving operator performance are supported by the interaction between the human and the system. Similarly, a key ingredient of success

in developing expert systems according to Berry (Berry, 1994) is involving users from the beginning of the development process in the specification and development of systems. Weisberg and Lanzetta (Weisberg & Lanzetta, 1991) state that the highest risk approach to design occurs when no input from the intended users is collected and used as a basis for the new system design. Thus, during the last decades, regulatory bodies in different fields have requested an increased focus on the application of the HF process in developing different HSI systems for professional use (Balfour et al., 2012; dos Santos et al., 2011; Hjelseth et al., 2015; Schaeffer, 2012).

I have organized this subsection according to the different levels of design activity in which the human factors perspective and human-centered design approach may take place, that is, 1) organization, 2) process, and 3) tool-level perspectives for system design. These three levels of the human-centered design approach are discussed in more detail below.

2.4.1 Organizational perspective

Even though human-related accidents and breakdowns in the operation of safety-critical systems have generally led to efforts to pay more attention to the human and social aspect in design, it is often found that the design of large systems does not meet their original deadlines, cost estimates and other expectations placed on them (e.g., improved productivity or usability). Mumford (Mumford, 2006) has suggested that one reason for this is the lack of a sociotechnical systemic approach in design. This insufficient understanding leads to an inability to fully recognize and acknowledge all the social and organizational complexity that is inherent in these operating environments. In addition, it has also been seen that in some design projects, the pressure to deliver the systems within budget and on schedule causes insufficient attention to be paid to human factors considerations, later backfiring on the operation of the system (Madni, 2010). Healey et al. (Healey et al., 2013) also argue that the operations of organizations may drift away, unnoticed, from the system engineering and human factors standards that they still believe in and strive to achieve. One possible reason for the rise of problems that has been suggested is that the operating organizations are not able to specify their needs and requirements to the designers and vendors. Thus, the commercial interests of providers may become the driving force of development, instead of the working conditions of those who will eventually use the system on a day-to-day basis (Senyucel, 2008). Damodaran (Damodaran, 1996) notes that in the context of large IT systems, the vendor often designs the system with a standardized situation in mind, and as a result the final design solution does not meet the practical realities of users' working tasks and conditions (Damodaran, 1996). A lot of history and experiences from industry projects suggest that human factors input, and a human-centered design approach are needed throughout the system lifecycle (Samaras, 2012). International standards such as ISO 9241-210 (ISO_9241-210, 2010) provide general guidance on how to follow human-centered design principles and processes throughout the whole lifecycle of the system. The main aim of

these standards is to enhance human-system interaction. However, for example, Booher (Booher, 2003) has noticed in his investigations that efforts to engage in human factors engineering and uphold a user perspective not only help to avoid accidents and increase the performance of the system, but also may help focus the design activities and thus reduce overall project costs. Consequently, acknowledging human and social aspects in design may also benefit the organization to a larger extent. For example, Bruseberg (Bruseberg, 2008) noted that it is likelier that financial benefits will materialize when an organization follows a standard HFE organization and process in its development efforts and operation. Monk et al. (Monk et al., 1993) argue that the only way to get sufficient initial requirements to develop HSIs of a good quality and avoid later financial, technical and other pitfalls is to involve users.

Rationale behind participatory design and user involvement

When considered from the perspective of the participatory design tradition, many rationales have been suggested for why human and social aspects are important for organizations conducting complex system design. Historically, the participation of workers was considered as a political instrument that mediated the struggle between the company management and workforce (BANSLER, 1989). It was an organizational strategy and a way to empower the workers to participate in the design of their own work conditions and thus maintain and increase democracy at the workplace (Bjerknes & Bratteteig, 1995). Initially, participatory design also had to do with the introduction of new assistive technologies (e.g., production automation) at workplaces, which was a sensitive subject in labor-intensive industries. In that connection, participatory design strategy was an important means to gain the acceptance of workers related to the technologies introduced at the workplace (Wagner & Piccoli, 2007). Participatory processes may decrease user resistance to new systems and minimize potential technology shock when new solutions do not fit perfectly with the prevailing work practices (Johnson et al., 2008).

Later on, participatory design projects have had the aim of bringing end users' perspectives and their in-depth knowledge (about the context for the final use of technology) to the design of new systems. Gärtner and Wagner (Gärtner & Wagner, 1996) introduced three arenas for participation: 1) Arena A, the individual project arena, 2) Arena B, the company arena, and 3) Arena C, the national arena. Arena A concerns the design of a specific system and its functioning. Arena B (the company arena) in turn relates to developing the organizational functions and Arena C to the general nationwide legal and political frameworks that define the relations of various actors in the work context (i.e., industrial partners and workers) and set the norms for working life. Thus, the emphasis for carrying out participatory design may change and evolve over time. In the context of safety-critical systems, most studies report the rationale behind the participatory approach to be the integration of the knowledge and operating experience of expert users in the design (dos Santos et al., 2011). Of course, in the context of operating safety-critical systems, a more general national-level discussion is also necessary as public acceptance and opinions may significantly

influence the operating environment (e.g., use of nuclear power in electricity production).

Type of users to be involved

The question of who should be involved in design is central. Often, several interacting stakeholders and user groups are involved in the use of one individual workplace or system. Their interests, focus, and requirements concerning the work system may differ, but they are stakeholders whose opinions are all still at some level necessary to consider in the design. As safety-critical organizations are often large, a rich variety of stakeholders may be involved in terms of both number and type (e.g., maintenance personnel, administration, project members and management).

Obviously, in the safety-critical system-design context, one of the most important stakeholder groups consists of the expert users whose principal task is to operate the system and who may with their in-depth knowledge meaningfully contribute to the design of the system. However, this may be easier said than done. Many known difficulties are associated with eliciting expert knowledge for useful design specifications. Noyes et al. (Noyes et al., 2017) list some general reasons why working with expert users and eliciting knowledge is a difficult process to carry out. Firstly, instead of working on a basic level, expert users often rely on their subconscious when "automatedly" performing activities. Therefore, the experts may find it difficult to provide details and reasoning for all their actions. Secondly, articulating expert knowledge may be difficult, that is, what the expert has learned cannot fully be put into words and verbalized. Furthermore, potential overlearning and the discovered difference between the behavior that is verbally expressed and the tacit knowledge that then actually guides skilled operations may hinder the extraction of relevant user information.

Boring and Lau (Boring & Lau, 2015) argue that even though there are guidelines for the inclusion of the user perspective into safety-critical HSI design, they may not be especially well calibrated to the needs of industry and thus do not always optimally support practical design work. Money et al. (Money et al., 2011) reported an interview study conducted with 11 medical device manufacturers about user involvement in their product development processes. The results were not very positive from the human factors point of view. It was found that – maybe partly due to the very hierarchical structure of the hospital organization – the manufacturers mainly valued the opinions of senior health care personnel (i.e., medical doctors) even though they would have not been the actual end users of the medical equipment. The manufacturers thought that they were the most qualified persons to report the needs of the users. Another group that they listened to carefully was the purchase department, which had a lot of decision-making power. Some of the interviewed representatives of the manufacturers acknowledged that patients constitute a growing user group of medical equipment (due to increasing home care), but this group was hardly ever involved in the design phases of medical devices.

In safety-critical contexts, the daily work duties of expert users often keep them very busy. In addition, they may have a shift-work schedule that makes it even more challenging to involve them in design. Balfour et al. (Balfour et al.,

2012) recognized this difficulty in their study about participatory design practices within the Norwegian oil and gas industry. Even though the importance of the end-user perspective was acknowledged, the availability of expert users with relevant contextual understanding and expertise was found to be limited. Still, Balfour et al. recommend that several users should be involved, at least a minimum of three (Balfour et al., 2012). This number of participants would be extremely low in any other context, such as in an urban planning project, but in the safety-critical systems design context this is unfortunately often the reality. In an extreme case, such as totally new industrial installations, where the operative personnel (i.e., expert users) have not been recruited yet (there are no actual end users), Balfour et al. (Balfour et al., 2012) recommend using representative users that have experience of operating similar equipment but who are not necessarily the same persons who will eventually operate the completed system. However, this may not be a straightforward solution either, as these environments are often unique and there is a lot of variability in both their operation and how things are organized.

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In a study about the design of an endoscopic operating theater, Garde and van der Voor (Garde & van der Voort, 2010) discovered that the lack of expert participation was due to the medical specialists' patient care comes first and they rarely have time for innovative activities. For this reason, Garde and van der Voor (Garde & van der Voort, 2010) emphasize that participation needs to be supplemented by a transparent and well-structured decision model that enables efficient decision-making in the design project.

The above issues (e.g., availability and cost) are also discussed by Noyes et al. (Noyes et al., 2017) in the context of involving flight-deck crew in the design of a new warning system. According to Noyes et al., specific difficulties faced in involving these particular experts (i.e., aircraft pilots) in design are that the crew

may be unused to being asked opinions about their equipment and may find it difficult to make objective assessments of their everyday activities because they are too familiar with them. In addition, the pilots may have high trust in their aircraft and may be reluctant to question its features. Some crews may also be requested to participate in many different development projects, which may be tedious. The authors emphasize that time is valuable to flight-deck personnel and the elicitation techniques and methods for user involvement need to be selected accordingly.

However, the potential beneficiaries of the participatory design may include large numbers of parties other than the direct end-users of the system (e.g., technicians, secretaries, and maintenance personnel). For example, in the healthcare domain, in the design of intensive care units (Nykänen et al., 2016) or large electronic patient record systems (Silsand & Christensen, 2012), many other user groups have also been involved in the planning of systems, as fluent and efficient operation demands multidisciplinary cooperation, without neglecting the experiences of the patients and their families. In these projects, one central aim from the participatory design point of view has been to bring together a group of employees with a diverse set of skills and knowledge who can form powerful and wide-ranging design and development teams. However, the context of large socio-technical systems with a heterogeneous group of users with different kinds of backgrounds and experiences and increasingly unclear user roles also poses new kinds of challenges in relation to traditional participatory design approaches and methods (Leonardi, 2011). Slavin (Slavin, 2016) even questions the meaningfulness of placing the user into the center today if the users' interaction is not solely directed at interacting with computers, unlike in the past, but rather the computers are used to interact with other parties and things that may shape the system. Consequently, one may ask what kinds of new demands this (i.e., designing for all different participants, actors, agents) introduces to the development of safety-critical systems.

Forms of user involvement

A variety of forms of user involvement may be considered to belong under the general approach of human-centered design. At one end of these approaches, designers may be seen to be moving toward the users by conducting usability evaluations and testing (i.e., user-centered design approach) whereas at the other end the users are moving toward the developers and in some sense becoming co-designers and partners (i.e., participatory design) in the design process (Sanders et al., 2008; Steen, 2011). Going even further, Fischer and Giaccardi (Fischer & Giaccardi, 2006) and Giaccardi (Giaccardi, 2005) have presented the notion of Meta-design, which refers to users carrying out design on their own once the new design solutions are already being implemented in use. They further claim that users engaging in design on their own (i.e., Meta-design) is necessary because participatory design is only temporary in character and the practices are constantly evolving in ways that can never be fully anticipated beforehand by the designers.

One reoccurring way of defining the forms of user involvement was presented by Damodaran (Damodaran, 1996). She categorized user involvement as

broadly falling somewhere on the continuum of being informative – consultative – participatory (see Figure 4). At the other end of the continuum, user involvement is informative in nature, meaning that the users mainly provide design information, whereas at the other end they actively influence the design decisions, which is referred to as participative involvement.

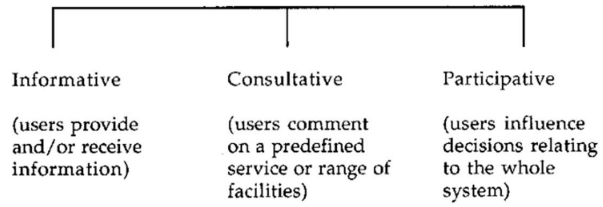

Figure 4. The continuum of forms of user involvement by Damodaran (Damodaran, 1996)

Another way to classify the levels of user involvement is as direct or representative participation (Haines & Wilson, 1998; Wilson & Haines, 1997). Involvement may be classified as direct participation if all those who will be affected by the new design solutions are involved and become participants in design. Representative participation refers to a situation where the participants are selected from a general population (i.e., they are likely users). Fuchs-Kittowski and Wenzlaff (Fuchs-Kittowski & Wenzlaff, 1987) have discussed user involvement within a framework in which they classify participation as consultative, representative, or consensus-oriented. Generally, this framework considers to what extent the users were involved and could influence the decision-making in the project. In consultative participation, the users may express their ideas and preferences, but the final decision rests with the actual design party and management. Like Wilson and Haines' (Wilson & Haines, 1997) representative participation, representativeness here means that elected members of the staff may participate, but the decision power rests with management. Involving participants in a consensus-oriented participatory design project refers to a situation in which all those involved in design may express ideas, and the final decisions are reached through negotiation and discussion (Fuchs-Kittowski & Wenzlaff, 1987).

A somewhat different angle on the form of involvement is to determine whether the participation is voluntary, imposed, or necessary (Wilson & Haines, 1997). Participation is often voluntary (i.e., each user can decide whether to participate), which is seen to create a good basis for collaboration. Participation may, however, be imposed, such as when it is built in as a part of continuous improvement programs, or necessary if no other way of developing the work setting is possible, for example due to limited resources.

Consequently, various forms of user involvement are possible within the scope of human-centered design, that is, everything from consulting users and other stakeholders to users becoming active design partners or even designers on their own. Thus, users can be engaged at various levels of commitment and intensity.

Obviously, safety-critical organizations also engage in human-centered design. Traditionally in these organizations, users are involved in testing of systems. An extensive body of research reports the results of usability studies where users may give feedback and participate in testing activities (Boring et al., 2015c; Braseth, 2013; E. Simonsen et al., 2020). Far fewer studies on safety-critical systems report earlier phases of design in which end users would have been actively involved. However, those examples that can be found have often promoted intensive user interaction and even recommended that users or their representatives be included in the design team (dos Santos et al., 2011; Hjelseth et al., 2015). In a safety-critical context, it seems that it truly is important to establish a relationship between the design organization and the operative personnel (i.e., operation experience). Furthermore, it is equally important to make this collaboration a long-term commitment that aims at continuous co-development of work instead of sporadic information exchange between the two (Suchman, 2002). However, enabling this kind of participation calls for recognition, resources and support from the organization and management as well.

Challenges related to user involvement in organizations

In the context of the design of safety-critical systems, some studies were identified in the literature review that discuss human-centered design and especially user involvement from the organizational point of view. For example, Balfour et al. (Balfour et al., 2012) reported a survey that they had conducted among six human factors experts working at the Human Factors Solution (HFS) consultancy to gather knowledge on participatory design within the Norwegian petroleum industry. The issues identified in the survey were further discussed in a brainstorming session, resulting in a table that aims to list the status of affairs, identified challenges and criteria for success in enabling participatory processes in the oil and gas industry. The recognized issues concerned all levels of participatory design – that is, the organization, process, and tool perspectives – that must be in place and carefully considered to carry out successful development projects. For example, even though regulatory bodies require participation throughout the process, in most cases user participation is still nowadays perceived as costly, time consuming and difficult to realize. Thus, the challenge is that the overall long-term benefits are not seen beyond the efforts needed in the short-term design process. To overcome these challenges, the authors suggest ensuring that all the parties involved in design are aware of the requirements (e.g., what is stated in regulatory demands) concerning user participation and inclusion of user perspective. In particular, the project owner should have awareness and understanding of these requirements. In addition, they advise (Balfour et al., 2012) that the participants should be provided with case examples where the participatory processes have been beneficial and the results that may be achieved when the users' perspective is appropriately acknowledged. The resulting table from the brainstorming session, however, does not go into detail on what kinds of tools and methods should be used to facilitate user participation. It is only mentioned that it would be beneficial if the users would

have an opportunity to experience some sample designs from other similar locations (i.e., benchmarking) and a possibility to exchange ideas and experiences with users from other locations employing similar solutions (i.e., peer support).

Garde et al. (Garde & van der Voort, 2010) have been studying the design of endoscopic operating rooms by means of a participatory design. According to them, the current practice is that team of stakeholders, supported by construction companies and vendors, design and carry out the operating theater development projects. However, Garde et al. (Garde & van der Voort, 2010) remark that disappointment regarding the final design solution is common, even though a sort of participatory design process (albeit a rudimentary one) is in place. According to the authors, the different stakeholders commonly think that all operating theaters can be alike and surgical procedures can be performed in any operating theater. However, as the authors point out, these kinds of assumptions are no longer valid in the era of high-tech surgery; complex computer-operated surgical tools such as robotics and navigation systems can only be utilized with optimal safety and efficiency if they are individually integrated in a dedicated workplace. Thus, in the operating theater design, user participation is crucial and needed.

This observation together with the evidenced problems encouraged the authors to carry out an interview study and a workshop to find out and discuss with stakeholders the reasons for failures in the earlier designs. The study revealed four key challenges in enabling participatory processes and reaching appropriate design outcomes: 1) an absence of a future vision in the hospitals, (2) a lack of genuine participation in the design, (3) limited insight of the stakeholders participating in a planning team into the consequences of design decisions and (4) a limited use of the knowledge and information available in hospitals. From these, the third recognized area of improvement – that is, the lack of insights into the consequences of design decisions – may be seen to be most closely related to the methods to be used to facilitate participatory processes, which are the main interest of this literature review. The authors suggest that several (e.g., scenario- or virtual reality-based) participatory design tools that suit the background and understanding of the participants can help them to anticipate the consequences of design decisions. However, these concrete tools are not discussed in any further detail and the tools are mentioned as one of the areas for future research and development.

Another study in the health care context by Bowen et al. (Bowen et al., 2013) sought to find out how people had experienced the participatory design project in which they had been involved earlier. The project was set up to develop better outpatient services for older people. In addition to the patients (i.e., older people), a variety of professionals from the hospital were also involved. The participants were interviewed and requested to describe their experiences of participating in the design. In the interviews, many issues and challenges related to the successful realization of participatory processes were identified. For example, there was some degree of dissatisfaction with the effectiveness of the project, that is, how and when change can happen. It was stated that one reason for this might be the complexity of the environment (e.g., how the aging physical

infrastructure fits with modern service demands). Furthermore, the lack of financial resources required to implement bigger changes was recognized as one key issue. External constraints were also discussed as a factor affecting the success of the participatory design. Even though representatives of many stakeholder groups were involved, there were still many more external parties; for example; national regulatory bodies partly define the process through which the changes can be initiated. In addition, the cost benefit of participation was questioned. According to the authors, one staff member thought that the participatory way of finding the problems seems like a lot of work, when one could just go and identify them individually, without all that effort. Some participants also mentioned that they felt like they were providing feedback on the design more than designing the solutions. This led the authors to conclude that further enhancement of participatory ideation methods would be necessary. They also stated that in a participatory design project, ensuring participants' strong ownership of making changes, fully engaging key decision-makers, and promoting an organizational culture of participation are essential considerations when planning the participatory design process.

Money et al. (Money et al., 2011) have investigated medical device manufacturers' points of view about the role of user involvement in their design processes. Eleven manufacturers were interviewed. The results were quite a disappointment. First, it was found that there was a mismatch between the users that were consulted and those that would in the end use the device in practice. Manufacturers tend to value the opinions of senior medical doctors even when those are not the personnel who actually would use the devices. Moreover, some manufacturers believed that the needs of the patients do not originate from the patients themselves. The patients seemed to be the user group whose opinion was valued least, even though the share of home use medical equipment is growing rapidly. Regarding the methods employed for user involvement, the manufacturers tend to use a very limited range of methods, mostly informal, such as discussions with doctors. Formal methods were thought to be too resource intensive and thus were not regarded as feasible, while informal methods were seen to offer versatile and rapid solutions. The value of the users' contribution to the design was not seen and such user-involving activities were mostly considered to slow down the development and add unnecessary cost and overhead to the project. Only one (out of eleven) of the interviewed manufacturers reported using formal methods to involve users. This employer had been inspired to do so by its employees who had participated in a university course on participatory design. Thus, it seems that the manufacturers also lacked the knowledge and expertise to carry out such user-involving practices.

Above, it has been recognized that organizations still have many challenges in accounting for user preferences and applying human-centered and participatory processes in their design. This does not, however, seem surprising, as Lu et al. (Lu et al., 2007) state that the human-centered and collaborative approach has not been well-adopted and practiced today even within the engineering domain. Lu et al. advocate a new engineering discipline called collaborative engi-

neering as an answer to the grand challenge of better understanding how engineers should collaborate to accomplish complex tasks that fulfill our ever-growing social responsibilities. The authors describe how in addition to the never-ending demands for products that function better and are cheaper and more sustainable – yet which are of higher quality and produced in faster cycles – the recent trends in lifecycle engineering and market globalization have introduced challenges into the engineering profession on a totally new scale. This calls for broader collaboration and shared understanding among different stakeholders. The authors state that even though the concept of collaboration is old, it is still nowadays taken for granted, misunderstood, and poorly accomplished in practice in design engineering organizations. Thus, even within the engineering domain, there is a need for a new mindset that is more human-centered and collaborative and based on joint decision-making. Realizing this shift in engineering practices may be an additional challenge for advancing user involvement and participatory processes. However, the roadmap for collaborative engineering developed by Lu et al. (Lu et al., 2007)– which pursues a shared understanding of the design team by exploring the definitions, objectives, and criteria and by co-constructing and negotiating agreements – seems to fall not far from the design principles that are familiar and characteristic to the idea of participatory design.

2.4.2 Process perspective

The process perspective is essential in considering how the participatory activities can be organized and integrated into the other design activities. The central idea in HCD (ISO 9241-210, 2009) is that the users' needs and preferences are considered in all stages of the design from initial concept development to the system in operation (see Figure 5).

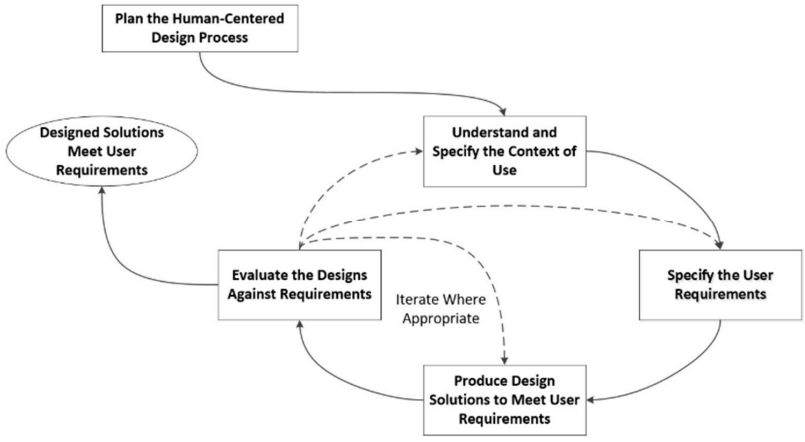

Figure 5. The human-centered design process as defined by the International Organization for Standardization (ISO 9241-210, 2009)

Similarly, the involvement of users may occur throughout the design process. The users can participate in exploring and evaluating the ideas, concepts, and

more mature prototypes. However, how these participatory processes are organized, timed, and documented may vary a lot between different design organizations. From the process perspective, for example, the relationship between the intensity of participation and the outcomes of these participatory events may lead to relevant questions – that is, what is the optimal level of participation and how should the limited resources for these activities be allocated within the design process to reach the best possible outcome?

The kind of process that would support HCD and participatory activities within it is described and outlined by many authors. According to Boy (G. A. Boy, 2011), HCD takes people into account from the very beginning of the design process. He states that it is not enough to consider only the system component; the interactions among the human and machine agents also need to be carefully analyzed. Boy has introduced the concept of active design documents (ADDs) to instantiate the human-centered and participatory process in complex design tasks in which several experts, including expert users, need to exchange vivid knowledge about design artifacts (G. A. Boy, 1997a, 1997b). According to him, ADDs are defined by three aspects: 1) interactive descriptions that tell how to use the artifact, 2) interface objects that enable simulating the use of the artifact and 3) contextual links that enable annotations of ADDs during usability evaluations. In the research on ADDs, the focus was on supporting user participation and capturing design knowledge so that the rationales behind the design decisions are made traceable in user accessible form.

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In addition to the two spaces, that is, the activity and the rationalization spaces, which were already introduced in connection with ADDs, DCs include two new spaces: the structure and function spaces (Figure 6). Within the rationalization space, the design rationale is described, and in the activity space, the current version of the system being designed is displayed in an illustrative and manipulatable form. In a structure space, the system is formally and declaratively described in the level of detail always possible at that point in time. A function space aims at describing the system being designed from the procedural and process dynamics perspectives.

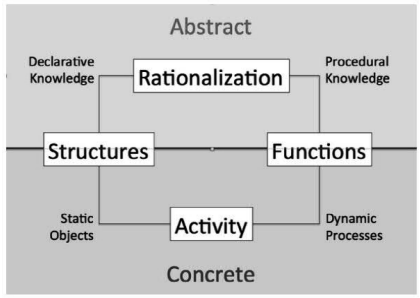

Figure 6. Process of moving between the different design spaces and between the abstract and concrete manifestations of the system being designed (G. Boy et al., 2016).

According to Boy, DCs are collaboratively created and refined from the beginning of the design process by the design team members. Thus, through the four distinct spaces, it gives a frame for the whole design process, but also supports documenting the system comprehensively from different perspectives.

Another example, in the context of nuclear installations and control room design, comes from dos Santos and his colleagues (dos Santos et al., 2011), who advocated a participatory ergonomics practice as one essential means of applying HFE in equipment design and addressing the human-centered design demands stated, for example, in NUREG 0711 (USNRC, 2012). According to dos Santos (dos Santos et al., 2011), human-centered design (i.e., incorporation of user needs in the design lifecycle) should start at the earliest stage of the development and continue iteratively until the system meets the set requirements. One practical example of the application of participatory ergonomics is given by dos Santos et al. (dos Santos et al., 2011; Farias et al., 2009) in a project that aimed at developing new fluorometer equipment for nuclear installations. Even after nuclear installation-related accidents and subsequent regulator recommendations that more attention must be paid to human factors and ergonomics, dos Santos et al. note that the design process is still predominantly technically driven.

As an answer to this, a systematic HCD methodology was introduced for the fluorometer design (Figure 7). The methodology included the following four main items: first, a profile of the multidisciplinary team (including end users) is defined, after which a work process for the team is described. Third, each team member is assigned specified tasks/roles, and finally a choice of ergonomics methods and tools is made to best serve the design project at hand.

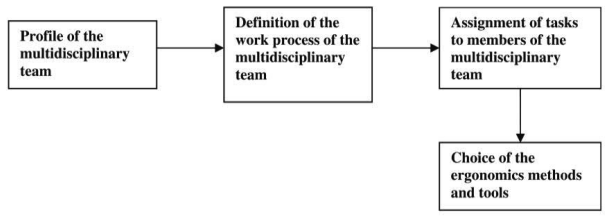

Figure 7. The proposed methodology of dos Santos et al. for participatory ergonomics (dos Santos et al., 2011)

The emphasis is on having a multidisciplinary team with a diverse set of expertise working together systematically from the beginning of the project. It seems that the design task may affect the kind of design process that is laid out for the given project. In the example of fluorometer design given by dos Santos et al., the process follows very conventional engineering practice from basic design starting with analysis of reference equipment, operational context, and functions to more detailed and integrated design phases in which the hardware, software and mechanical structures are defined, and finally formally tested and evaluated. However, according to dos Santos et al., from the participatory ergonomics point of view the most important aspect is to enable information sharing among the design team and carry out a continuous process of V&V to obtain/integrate relevant human and social understanding into the equipment design.

Tideman et al. (Tideman et al., 2008) present a new product design method that aims to support designers in determining stakeholders' preferences and finding the best compromise between those preferences. The new product design method also aims at giving non-designers (e.g., users and maintenance personnel, etc.) a proactive role by involving them actively in the design. According to the authors, the new product design method is based on seven recognizable trends that support the contemporary design process, namely: 1) performing (design and engineering) activities simultaneously, 2) considering design as a group activity, 3) involving intended users, 4) using scenarios in design, 5) stimulating creativity, 6) using virtual reality simulations and 7) using gaming principles. The core of the method is to establish a dedicated design environment that combines VR simulation, gaming principles and scenarios and in which users and other relevant stakeholder groups may be invited to participate in design. Within the dedicated design environment, all involved users and stakeholders are allowed to create their own designs/solutions and then immediately test these in a variety of use scenarios. The new product design methods include two main phases (Figure 8). In the first phase, the design environment is established and in the second phase, the good design is further specified.

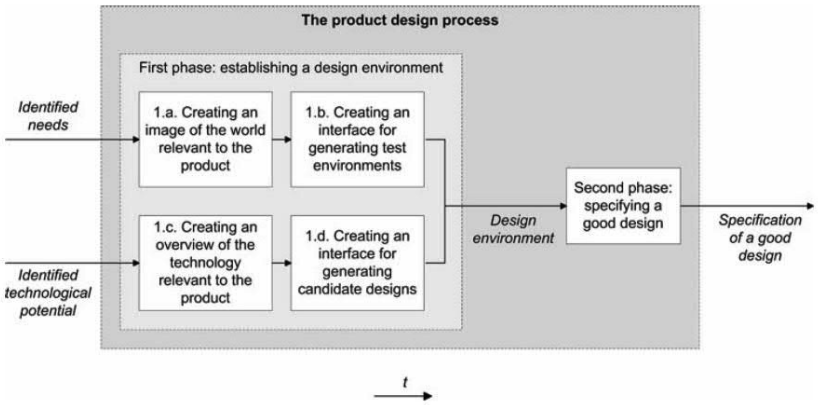

Figure 8. The process for applying the new product design method by Tideman et al. (Tideman et al., 2008)

According to Tideman et al. (Tideman et al., 2008), the designer has the main responsibility for creating the design environment (i.e., first phase). By observing the activity in the real environment, reading literature, and interviewing the users, the designer makes an educated guess about the necessary content of the simulated design environment. The users are then invited to refine the qualities of the environment in reflection sessions in which the goal is to iteratively work towards specifying the details. After a few iterations, the design environment is expected to reach a saturation point and no further alterations are needed; thus, the second phase of the design process can be proceeded, that is, using the environment to produce actual design proposals and identifying user preferences.

In the second phase, the different users and stakeholders are invited into the design environment. However, now they use the design environment to create actual candidate designs. The new design proposals and functionalities can then be directly tested and experienced by means of relevant simulation and scenarios in the design environment. The stakeholders' individual design proposals and the justifications behind them are recorded and then, through a review process, the designer aims at finding a compromise that acknowledges the different stakeholder preferences.

Creating the design environment with relevant simulations and characteristics seems to be a laborious and time-consuming process. However, once realized, it enables users to experience the qualities of their own design in a very tangible form. The described new product design method also leaves the designer with the responsibility for finding the final solution. In addition, the stakeholders seem to contribute individually instead of the design being a truly collaborative group activity in which ideas and thoughts would be shared with the design team.

Fogli and Guida (Fogli & Guida, 2013) introduce a new approach called knowledge-centered design and apply it in the context of emergency response and particularly in the design of a Decision Support System (DSS) for pandemic flu emergency management. They suggest that the knowledge-centered method complements the more established human-centered design and activity-centered design approach by acknowledging the wider context in which the application will be employed. According to the authors, knowledge-centered design puts knowledge in the center (i.e., knowledge about the users of the DSS, their activities, and the use context of the DSS). Moreover, a participatory approach to design is promoted. Fogli and Cuida (Fogli & Guida, 2013) state that the core of knowledge-centered design is the consideration of the different kinds of knowledge that are involved in the design of a DSS, namely: 1) knowledge about the target environment where the DSS will be used, 2) knowledge about the user tasks, and 3) knowledge about user profiles and interaction patterns. Eventually, functional modeling is performed to specify the functions that the DSS is expected to provide. The knowledge-centered design phase (i.e., inner cycle) (see Figure 9) is followed by a development phase (i.e., first part of the outer cycle) in which prototypes of different kinds are developed. As the final phase, an evaluation (i.e., second part of the outer cycle) with the end users is carried out to confirm that the new DDS design meets the set requirements.

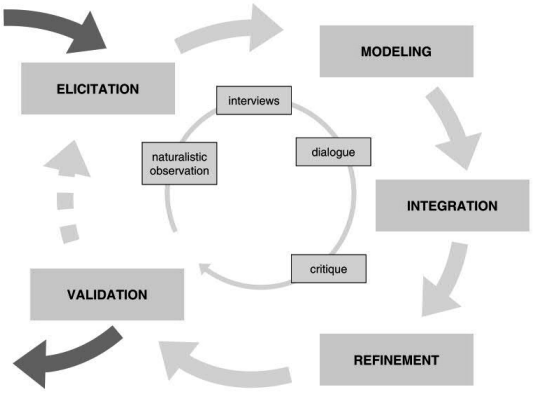

Figure 9. Knowledge acquisition process by Fogli and Guida (Fogli & Guida, 2013)

In the example case of pandemic flu emergency management, a variety of user and stakeholder groups were identified and involved (e.g., event managers, local emergency managers and field operators) in the design. However, even though the authors explicitly claim to promote participatory design processes, they do not describe in detail what participatory methods were used and through what kind of procedure.

Boring et al. (Boring et al., 2015b, 2015a) also discuss the value of expert users' knowledge in the control-room design context in the nuclear domain. According to the authors, there is a guidance gap in the human factors evaluation process in the nuclear domain, which led them to develop and introduce the Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE) approach to be applied particularly in control room modernization projects (for more detailed descriptions, see (Boring et al., 2014; Boring & Joe, 2015)). First, the authors state that there are three types of evaluations that may be helpful in achieving successful design outcomes: expert review, usability testing and knowledge elicitation. With knowledge elicitation (also referred to with the term "epistemiation"), they mean centering on the users' experiences and insight on using the system and actively bringing these into the design process. According to the authors, another view on human factors evaluations is provided by the phasing of the evaluation, that is, in what phase of the design process the evaluation is implemented. The regulatory guidance has its main focus on late-stage evaluations (i.e., summative evaluation) that aim to confirm the success of the design. The evaluations during and especially in early stages of the design can be seen to be formative in nature, that is, evaluations that produce design feedback that helps in shaping and improving the design solution. Based on these considerations on human factors evaluations, Boring et al. present the GONUKE process, which comprises 12 individual steps of evaluation that are summarized in Figure 10.

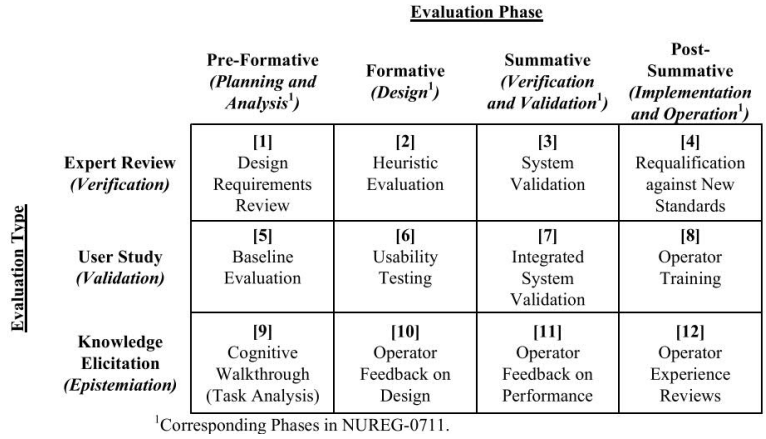

Figure 10. The GONUKE process comprising types and phases of HF evaluations (Boring et al., 2015b)

The authors state that epistemiation (see the lowest row in Figure 10) in the sense of gathering expert user feedback is not a common tool in usability engineering and human-centered design and that they are actively working on developing its applications to support control room evaluations. The authors' conceptions about the potential value of expert users' contributions and the underdeveloped methodological base for its better design integration corresponds to a great extent with what is presented as motivating the research work in this thesis.

Andersen and Broberg (Andersen & Broberg, 2015, 2017) have studied a method called participatory simulation – which combines participatory ergonomics and simulation – in the hospital context from the knowledge creation point of view. They note that the majority of participatory simulation studies have concentrated on analyzing the outcomes of participatory activities but have paid less attention to the process of creating these outcomes. According to them, understanding the process would be important so that the participatory activities would not be just "blindly" planned and facilitated. They state that understanding how to create a participatory simulation process that would result in the wanted outcomes, that is, gaining of new ergonomic insights and design specifications, would better justify involving healthcare professionals in participatory activities and assigning their time to activities that are outside their core area (i.e., patient work). Knowledge creation in this study was understood as a process of converting individual tacit knowledge (i.e., experiences, values, contextual information, and expert insight) into explicit common knowledge and back again into tacit common knowledge in the organization. Moreover, three key elements that also formed an initial analysis frame for the study were: 1) interaction with objects in the form of simulation media, 2) engagement in tests and experiments and 3) sharing knowledge in the form of experiences. Andersen and Broberg carefully analyzed the knowledge creation process in three different hospital development projects in which participatory simulation was used for interacting with the different user groups, and based on this developed

a framework (see Figure 11) that describes the process of how ergonomics knowledge is created in participatory simulations.

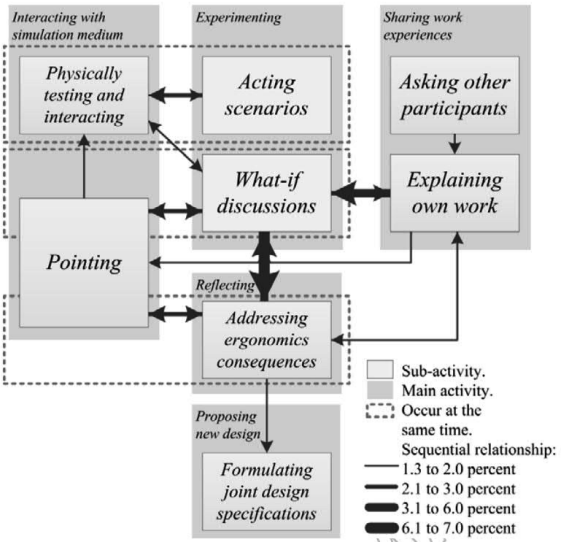

Figure 11. Knowledge creation framework in participatory simulation by Andersen and Broberg (Andersen & Broberg, 2015)

They summarize their main learnings from the participatory simulation by giving four recommendations. First, they emphasize the importance of encouraging the participants to talk about and explain their work so that the externalization of work experiences can be fostered. Secondly, both scenario acting and what-if discussions should be planned to be included in the experiments within the participatory simulation. Third, the selection of simulation medium (e.g., paper mock-ups) should also be done to allow acting out of scenarios and what-if discussions to take place. Lastly, the participants should be actively given opportunities to reflect on the ergonomic consequences of the experiments (Andersen & Broberg, 2017). The value of this study is in analyzing and explaining knowledge creation in the participatory process so that it can be better understood how and through what kinds of questions user feedback relevant to design be elicited. The authors mention that the studies have been done in the hospital context; however, the learnings might be relevant and applicable to the design of other work systems as well.

In the healthcare context and in particular with respect to connected health devices, Harte et al. (Harte et al., 2017) have also promoted the human-centered design methodology. According to them, in the medical system design process, the Agency for Healthcare Research and Quality and the Food and Drug Administration (FDA) require a human factors perspective and user involvement in design. The authors, however, note that there are some specific needs related to the human-centered design of connected health devices. Firstly, they state that the medical literature is lacking detailed methodological descriptions and structures for human-centered design, which causes the practices to vary greatly.

Secondly, they note that the health industry is fast-moving and highly competitive. Thus, even though the developed devices need to reach high levels of usability, their development cycles also need to be very rapid. Medical applications are introduced online at an accelerating pace, but they can also become relatively obsolete in a short period of time. Lastly, the authors state that design documentation is essential, as the products need to adhere to different standards to gain permits for market launch. Taking into account the abovementioned needs, and those requirements that are already stated in ISO 9241-210 about human-centered design (e.g., proper understanding of users, tasks and environment, iterative user involvement and evaluations throughout the design, acknowledging the whole range of UX, and involving a multidisciplinary design team), the authors present a new human-centered design methodology for connected health device design (see Figure 12). The methodology includes three main phases: 1) establishing the context of use and user requirements, 2) expert inspections and walkthroughs and 3) usability testing with end users.

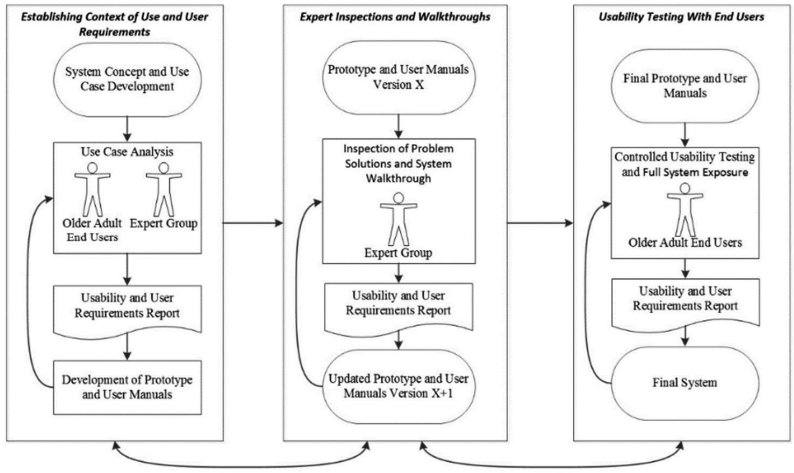

Figure 12. Three-phase HCD methodology for designing connected health devices (Harte et al., 2017)

Already in the first phase, the method aims to produce concrete prototypes that can be discussed with the end users, which according to the authors enables early user feedback and the acceleration of the design process. In the second phase, the end users are not directly involved; instead, a multidisciplinary expert team evaluates the proposed design. This is because the authors are cautious about exposing a more mature prototype to a potentially vulnerable user group (e.g., older adults or children) until it has gone through proper inspection by experts. This is maybe the main difference: the primary end users (i.e., patients) are not seen as experts what comes to the safety relevance of design solutions. Applying this methodology to, for example, nuclear equipment and HSI design would require end user (e.g., operator) involvement in phase 2 as well. However, the emphasis on documentation practices can be seen as an advantage of this methodology.

2.4.3 Tool perspective

The main interest of this literature review is in user involvement and participatory processes in safety-critical system design and especially at the practical level of doing the design work. Thus, the perspective of participatory design tools and methods is particularly important. Participatory design is an approach that uses qualitative methods to directly engage people in the design of systems they will use (Blomberg, J., 1993). A variety of concrete participatory design tools and methods exist to facilitate the interaction and co-design activities within the design team. Still, many studies report that the outcomes of participatory design activities are not always as successful as was intended. In addition, even though these aim to be participatory processes, some participants have experienced that their contribution consists more of design input (i.e., design feedback) than actual design activity (Bowen et al., 2013). This may be disappointing for the designers and human factors experts who aim to involve users in a more influential role in the design. Thus, it would be important to better understand the different co-creation tools and their specific characteristics to guide the selection of a best-suited set of participatory methods for the design task at hand. Below I have used Damodaran (Damodaran, 1996) categorization for forms of user involvement (i.e., informative, consultative, and participatory) in presenting the tools and methods reported in the literature.

Informative form of user involvement
The users' needs and preferences should be used for informing the design of safety-critical systems. Different types of *field study* and *ethnographic methods* often involve users in an informative way in the design, meaning that user information is gained by, for example, *interviewing* and *observing* the users in their real working environment and using this information as a basis for eliciting user requirements. These types of user inquiries are common and successfully used to inform human-centered design and include methods such as field observation, a number of interview techniques and questionnaires/surveys.

In the nuclear context, Gatto et al. (Gatto et al., 2013) have studied the use of virtual simulation in ergonomic evaluation of PWR NPP control room environments. Their specific interest was on the positioning of monitoring and control equipment in the control panels and desks and what impact this has on elapsed times spent by operators in controlling the system. The authors stated that the configuration of control buttons and monitoring displays may directly affect how easily the different process variables and alarm indications can be identified and appropriate actions initiated during operation. In the nuclear context, the time from the drawing board to the point when the human operator can concretely experience the impact and the qualities of the different interface elements is often very long. However, the authors state that it would be more efficient and useful to obtain user feedback to inform design already in the earlier phases of the development process. Thus, an ergonomic study was conducted in a CR environment that was realized with virtual reality technology, after which the results were compared with earlier ergonomic evaluations in the real CR environment. The aim was to find out if the virtual reality-based CR could serve as

a platform for early evaluations and provide valid user feedback that could inform design.

The results of this comparative analysis of operation in the VR and real CR environment showed no significant differences in findings between the two setups, except for three tasks. In these three cases, the elapsed times were shorter than the times in the real CR environment, but according to the authors these differences could be explained by the shortcomings of the simulation environment (e.g., avatars' movements were limited). Overall, the authors concluded that the results indicated that the VR based CR environment is a valid tool for estimating the operators' action elapsed times and the physical characteristics of the CR and its interfaces. Thus, it potentially enables the early integration of the human operator perspective in CR design. The authors state that the evaluation may be first carried out cost-efficiently in a virtual environment before taking the effort to conduct an evaluation in a real physical simulator facility.

Consultative form of user involvement

Bjørneseth et al. (Bjørneseth et al., 2012) completed an explorative study that aimed at developing an interface for dynamic position application in a maritime context. A new way of directing multitouch gesture interaction was studied by applying methods and tools of human-centered design. The authors' main motivation was to find interaction techniques that can benefit the user experience onboard. In the first phase of the project, a background study (including end user interviews and a guessability study) was conducted to define a suitable set of gestures for interaction and to understand the demands of dynamic positioning in vessel operations. Carefully following the human-centered design process, iterative design-evaluation activities were carried out to refine the details of the interface. After this, a more comprehensive evaluation of the new interface was executed in a motion platform configured to simulate sea conditions on vessels (i.e., simulator testing). The study aimed to test four main hypotheses: 1) multitouch gesture interaction will lead to faster interaction; 2) multitouch gesture interaction will reduce errors; 3) multitouch gesture interaction will lead to more situational awareness; and 4) multitouch gesture interaction will be less affected by a moving environment. Contrary to the initial background studies, in the final evaluation student participants were recruited to use the new interface (user testing with prototype).

The results of the final study did not provide much support for the four hypotheses and the compared soft-button interface was preferred. The results also clearly indicate that environmental motion (i.e., weaving) affects gesture input negatively. However, the authors thought that the study exemplified the importance of the human operator perspective when planning to apply new technologies and designing interfaces for safety-critical operation. The initial users' opinions and preferences were consulted in a very early phase of development. Even though the users involved in the testing were just maritime students (not expert users), they provided critical user information related to the suitability of touch screen technologies in the maritime context.

In the hospital context, the University Hospital of North Norway initiated a study on work processes, resource usage and error rates related to their laboratory activities. The study revealed a lot of repetitive work and many mistakes being made in handling paper-based laboratory requisitions. This led to a project reported by Johannessen and Ellingsen (Johannessen & Ellingsen, 2008) in which the aim was to design an (IT) system that would function as the main interface between local practitioners and the hospital laboratories from which the practitioners could order laboratory services for their patients.

The vendor of the system was a company called Well Diagnostics. It used agile methods in its software development as many companies developing large IT systems often do. The central means of acknowledging the user perspective in an agile development process is the utilization of user stories. One cycle in an agile development process takes three weeks, during which the relevant user stories are identified, prioritized, and scheduled to be realized within different iteration cycles. The code for different functionalities in user stories is written and the product is implemented and tested by the users. Then the code is repeatedly refined until the user story is satisfactorily fulfilled. Piloting of new functionalities is done by means of a pilot channel in which pilot users may test the system safely. Often the user stories are written by the user organization and the stories are the main communication channel between the developers and the customer. In Well Diagnostics' process, the user stories were written by the developers, and feedback on them was requested from the customer. However, this created a challenge when faced with the development of a system with many user groups that use the system in various ways and have diverse work practices. In the first phase of development, the focus was on the user stories of the local practitioners. One important new user group was discovered in this process, that is, the receptionists that do a lot of work prior to the patients' visits and may also order laboratory tests. In the second phase, the developers faced even larger groups of users when the hospital side of the laboratory services delivery chain was concentrated. In the final phase of the project, the commercialization phase, the new system was taken into use. Since the release, other hospitals have also purchased the system, imposing the vendor again new challenge, as it has to account for several new customers and an even larger number of users.

Participative form of user involvement

The participative form of user involvement moves from the technical system descriptions that are traditionally central in design to collaborative construction of mock-ups, prototyping and game-like participatory design sessions. Thus, the different maturity levels of prototypes and workshop formats serve as a focal point for collaboration and knowledge sharing among the participants. For example, Barcellini et al. (Barcellini et al., 2015) promote implementing a participatory design process that enables setting up spaces in which the different levels of abstraction of design concepts and ideas may be discussed. Furthermore, the design cards introduced by Guy Boy (G. Boy et al., 2016) aim to support collaboration between the design team and describe the system being designed from

multiple perspectives (i.e., activity and functional) and not only from the structural point of view. In the participative form of user involvement, the users actively participate in making design decisions instead of just providing opinions.

In the nuclear context, dos Santos et al. (dos Santos et al., 2008) present a methodology for carrying out control room design in a way that acknowledges well-structured and relevant human factors principles. According to the authors, these efforts should cover all phases of the CR lifecycle, from conceptual design to the decommissioning phase. The proposed methodological framework applies human factors guidelines and standards, checklists and ergonomics as an aid tool and serves as a basis for proper analysis of operator activity. The authors state that as poorly designed CR environments and interfaces may have deleterious impacts on the success of operator work and decision-making, one main purpose of human factors analysis is to identify HSI issues and difficulties the operators have with control equipment and propose improvements and reshaping of operator tools.

In the study, the methodological framework was applied to develop the HSIs of an experimental facility for human factors research, the Human–System Interface Laboratory (HSIL). The objective was to obtain human-centered data using the framework in the evaluation of the existing interfaces to support the design of the new HSIs. The main phases of the framework are: the tasks description, integrated evaluation of the existing interfaces, development of the new interfaces and integrated evaluation of the new interfaces. In the different phases, a variety of tools are used, such as expert reviews, surveys, and checklists.

Following through the framework, a list of interface deficiencies could be summarized. The list included four main topic areas of needs for improvements: the alarm system, screen information, screen components and screen visual appearance, navigation and controls. This information was then utilized in the development of the new HSIs (prototyping), and many redesigns were introduced in the process. The evaluation of the new interface was carried out by observing and analyzing the operator activity and executing expert review (done by two operators) with a checklist procedure. The new interface was found to have some advantages over the existing one regarding its conformance to the NUREG 700 guideline (checklist), to the decrease of elapsed/interval times in executing operations, and to the results of the user satisfaction questionnaire. The design tools (expert review, checklists, questionnaires, and task observation) used in this specific project were quite conventional. However, the expert users (i.e., operators) were involved in the design team throughout the project and they participated actively in analyzing the old and new interfaces. The project seemed to result in a successful outcome in terms of improved interface design.

Similar to the other forms of user involvement, most of the human-centered design projects that can be numbered among the participatory form conduct *field observations* and *interviews* in the beginning of the design process in order to obtain a better contextual understanding of the design task. Then, the users are most often involved in the design in various types of *design workshops* and *focus group sessions* (Hossard et al., 2013; Manen et al., 2014; Österman et

al., 2016). For example, Hossard et al. (Hossard et al., 2013) used a participatory approach to design spatial scenarios of cropping systems and assess their effects on phoma stem canker (i.e., plant disease) management at a regional scale in central France and used a six-step method in which different types of *workshops* were the main arena for involving users. Each of the organized workshops had a different focus. In the first workshops, the aim was to build *a shared vision* of phoma functioning and acting. The second set of workshops concentrated on the design of *scenarios*, and the last workshops were evaluative in nature and provided the participants with the possibility to experience the effect of the different scenarios by means of *simulation* and *numerical modeling*.

In many of the participatory design workshops, different types of mock-ups were used as a central tool to involve users in design (dos Santos et al., 2011; Jeffery et al., 2017). Several research studies have also explored the power of different mock-up media to reveal critical user needs and preferences regarding the design task (Andersen & Broberg, 2015, 2017; Jeffery et al., 2017; Österman et al., 2016). For example, Andersen and Broberg (Andersen & Broberg, 2015) studied participatory simulation with the help of three different mock-ups (i.e., 3D paper mock-up with Lego figures, physical size foam mock-up and a blueprint paper mock-up with Lego figures). They used video recordings from three different participatory design projects in a hospital context and analyzed them from the knowledge creation perspective (i.e., what kind of ergonomic information and design specifications the mock-ups may allow the users to jointly formulate). They recognize that the workers' professional knowledge is often tacit in nature and may be difficult to verbalize. Thus, understanding how the different mock-ups can help elicit this information is important in planning the participatory activities. Their analysis revealed three essential elements that need to be in place in a participatory process: participants sharing work experiences; experimenting with scenarios; and reflecting on ergonomics consequences. In this experimenting–reflection loop, the mock-ups may play a facilitating role and enable diverse discussions to take place. When analyzing the modes of interaction (i.e., pointing, and physically testing and interacting) with the three different mock-ups, however, no clear differences could be identified between them. In the study, all the mock-ups supported to some degree the two modes of interaction. However, the participants preferred least the blueprint mock-up; one reason may be that it did not afford good possibilities to physically experiment with different patient room setups.

A number of participatory studies experiment with scenario design, prototyping and different kinds of gaming/simulation principles in order to involve the users in the design of new work systems and tools (Andersen & Broberg, 2015; Broberg & Edwards, 2012; Hjelseth et al., 2015). For example, one interesting participatory design study by Björgvisson (Björgvinsson, 2008) in the context of an intensive care unit (ICU) involved the personnel in developing new informal learning practices. The author suggests seeing design as a joint inquiry into prototypical practices, which requires an engaged open-ended inquiry into future practices without a strictly defined a priori view of what technologies or process designers should aim for. It demands the participants to carry out small

in-situ experiments and being sensitive to whether any relevant practices may be invoked. In the specific intensive care unit project, the possibilities of new information technology to support personnel in updating relevant new knowledge were explored.

In the design workshops with the intensive care unit's personnel, the participants played a design games called The ICU as a Family and Garden, which were created especially with this case in mind. The game playing in the workshop resulted in one critical notion, that is, that the knowledge gained bedside and the knowledge developed within the various competence groups did not spread well enough in the clinic. Different kinds of aids were ideated for this issue in the clinic in the workshop. Promising ideas were briefly explored and tested by some of the participating nurses, and subsequently it was decided that the focus of the project would be to study how a self-produced videos could support the sharing of knowledge gained through experience at work. Following that, a set of prototype videos were produced – these were watched during in-situ experiments as a part of the clinic's day-to-day work practices. The project provides an example of an open-ended design process in which the direction was not very clear at the beginning, but which in the end produced a new complementary learning aid that was a good fit for the clinic's work practices.

Hjelseth (Hjelseth et al., 2015) provides an example of another design project in which participatory design and *gaming principles* (i.e., real-time 3D game engines) were used for exploring possible futures in the maritime domain. One of the specific design cases in this study was to develop *a concept of operation* for future crisis management in Oslo Fjord. According to the author, now the Oslo area is the most hazardous coastline in Norway, and an increase in traffic might add considerably to existing risks and challenges. Thus, a participatory project was initiated in which different stakeholders from the Oslo Fjord were invited to discuss the challenges and develop solutions for future operation. An *advanced 3D game engine* and *simulation* was used to facilitate *scenario* exploration (e.g., intense traffic situation, crossing cruise ship and bulk transportation and collision situation) in the design sessions. The design sessions resulted in several new ideas for crisis management, for example ideas concerning pilot training programs and a new collision warning system. Regarding the benefits of using *gaming principles* and simulation to facilitate participatory design sessions, the author concludes that a realistic and accurate scale between objects and landscape could be created with the game engine. The participants could also easily change the viewing perspective (between a first-person view from the ship bridge and an overview of the fjord), which triggered more precise questions and notions about the situation. Moreover, the ability to add or change the *scenarios* during the simulation led the participants to provide more precise input on the risk factors in the scenarios. Overall, it seems that the new advanced *3D visualizations* and *simulation* may provide a more immersive environment for the participatory processes (i.e., designer–user interaction) to take place.

If Björgvisson (Björgvinsson, 2008) above was promoting carrying out small scale in-situ experiments, Simonsen and Hertzum (J. Simonsen & Hertzum, 2008) present a sustained participatory design process and call for developing

methods that would allow *large-scale testing* in real environments (i.e., expose mature prototypes to real work practices) as a part of the design. The authors admit that in safety-critical contexts this may be more difficult to realize but would be necessary to avoid costly problems and issues that may appear later in the implementation phase if the new solutions are not properly experimented and tested in earlier design phases. Overcoming these testing restrictions in safety-critical environments, the authors suggest the use of some kinds of simulation or shadowing techniques, for example. In their own study (J. Simonsen & Hertzum, 2012a) in the healthcare context, they used an *advanced prototype* of a new Electronic Patient Record (EPR) (that had for safety reasons some parts simulated by a back office using *Wizard of Oz techniques*) in a stroke unit for a five-day period. The experiment required all paper-based patient records in the stroke unit to be replaced with the EPR system. For the experiment, extensive planning activity and training of the unit's personnel for EPR were required. However, the experiment and the efforts needed were deemed to be necessary, as so many difficulties had been encountered in the earlier implementation of other EPR subsystems related to drug management. Already during the five-day testing period, some positive changes in the department work practices were observed. For example, at departmental meetings the head nurse had earlier read out the patient statuses from paper-based patient records, but now thanks to EPR the whole nurse team could view the statuses collaboratively from a shared large screen display. As everyone could read the details and make notes, this created a good basis for improved awareness of the department's overall situation. The authors promote *large-scale experimenting* with *matured prototypes* in real work environments and recognize the need for methods that support *stepwise testing* and implementation, as in their view it is no longer realistic to rely on any other way of introducing new technological tools at contemporary workplaces.

2.5 User involvement in the design of safety-critical systems

In the following subsection, I review studies on the participatory design of safety critical systems. The particular focus is on experiences of product-level participatory processes. Primary studies carried out in the NPP context are reviewed; studies from some other safety-critical contexts are also included. The aim was to find out how participatory design and user involvement are carried out in practice in the context of safety-critical system design – for example, what kinds of design solutions are targeted, with what kinds of methods are users involved, and what kinds of outcomes the participatory design projects have achieved.

As only a very limited number of studies concerning participatory design and user involvement in the NPP context were identified in the literature, in the following both the NPP-related studies and those from other safety-critical domains are reported together. The scope of the system and the point in its lifecycle in which the users were involved in design varied: In some studies, the users were involved at a very early stage of design (i.e., operating experience review or concept phase) whereas several studies were carried out in a phase in which

the designs are evaluated. In a few studies, the design took place when the system was already in use. In the following, the studies are organized according to the phases of the design process (i.e., early phase, evaluation and in use) in which the users were involved.

2.5.1 Studies involving users in the early stage of design

Studies in which the user involvement and design concentrated on the early phase of development were reported by dos Santos et al. (dos Santos et al., 2011), Boy (G. Boy et al., 2016), Österman et al. (Österman et al., 2016), Hjelseth et al. (Hjelseth et al., 2015), Mackay et al. (Mackay, 2000; Mackay et al., 1998), Tideman et al. (Tideman et al., 2008), Björgvinsson (Björgvinsson, 2008) and Kusunoki et al. (Kusunoki et al., 2015).

In the context of nuclear installations and CR system design, dos Santos and his colleagues have advocated a participatory ergonomics practice as one essential means to apply HFE in equipment design. According to dos Santos (dos Santos et al., 2011), human-centered design (i.e., incorporation of user needs in the design lifecycle) should start at the earliest stage of the project and continue iteratively until the system meets the set requirements. One practical example of the application of participatory ergonomics is given by dos Santos et al. (dos Santos et al., 2011) in a project that aimed at developing new fluorometer equipment (a device that measures an unknown amount of uranium) for nuclear installations. In the fluorometer design, the systematic methodology referred to and introduced in subsection (2.5.2) above was used. In this particular design project, two end users (i.e., licensed CR operators) participated and were assigned as members of the multidisciplinary design team. The main task of the end-user representatives was to provide information to team members in response to questions related to their work activities, needs, work practices and operation experiences of similar equipment. Figure 13below depicts the ergonomic methods used in the fluorometer design in detail. At the beginning of the project, the project team allocated different activities regarding the specific phases of the fluorometer lifecycle (see levels 1 and 2 in Figure 13). In level 3, in Figure 13, the methods used to collect performance data of the users are specified.

One example of the particular way in which the users participated in the project was that the analysis of the reference equipment (activity) was performed by means of interviews and talk-through with the users. In specific, as the users performed simulated tasks, they provided information to the multidisciplinary team in response to questions. The general aim in this activity was to identify points in the human-system interaction where the equipment design did not complement user goals. The questions posed in order to facilitate and focus the information needs specification included: Why did you do that?; How did you do it?; What were the preconditions for doing that?; What information did you consult for doing that?; What were the results of doing that?

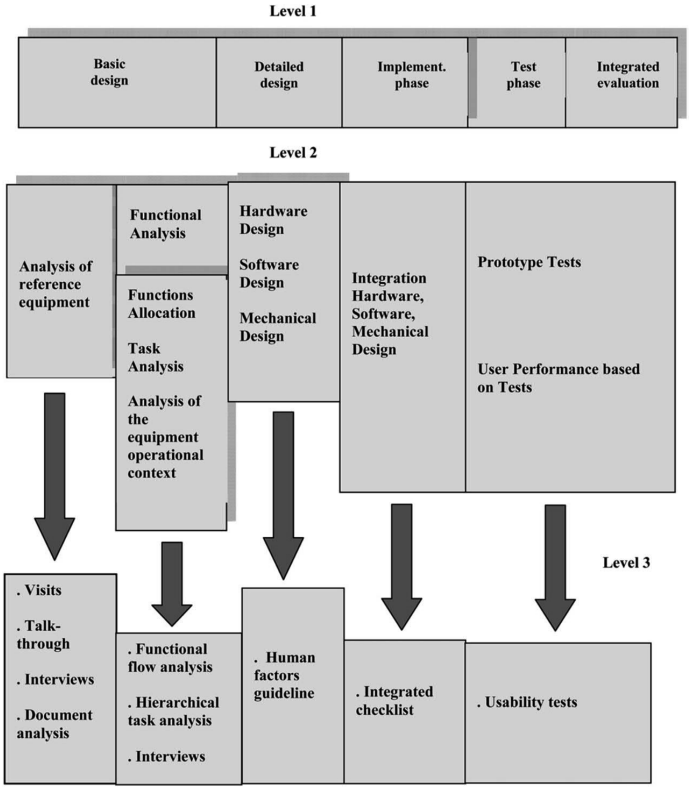

Figure 13. Ergonomics methods used in fluorometer design (dos Santos et al., 2011)

In basic design (lifecycle phase), the users were also actively involved in functions analysis and functions allocations with the human factors expert and the design engineers participating in the project. This analysis aimed at a more detailed characterization of the working environment, the users, and their needs. In the following lifecycle phases – that is, the detailed design, implementation, test and integrated evaluation phases – the aim of the design team was to produce prototypes of different maturity levels and perform verification and validation tests. The validation process demands that users participate in the performance of real tasks with the proposed equipment design in the working environment. The aim is then to validate the equipment design, define possible usability problems that may have a negative impact on user performance and specify the need for procedure design. In general, the authors conclude that the use of participatory ergonomics in the nuclear industry presents many opportunities for improvements, such as with respect to system effectiveness, efficiency, and safety of operations.

In the fluorometer design case, the overall results showed a positive and significant contribution of participatory ergonomics. Especially, the integration of end users' knowledge about the equipment in the design was experienced to be crucial and useful in achieving the operational goals. According to the authors, the project reflects the importance of having a multidisciplinary group of professionals (i.e., representatives from diverse fields of knowledge and with differ-

ent technical capabilities) who together take decisions and design the equipment. Moreover, the authors claim that participatory ergonomics may only yield its full advantages if followed throughout the product lifecycle.

Boy et al. (G. Boy et al., 2016; G. A. Boy, 1997b, 1997a) have also conducted a lot of research and design work in the context of safety-critical systems such as aeronautics-related domains and the nuclear domain. Boy et al. (G. Boy et al., 2016) have introduced a methodology called Active Design Documents (ADD) and later extended it with the notion of Design Cards (DCs). According to Boy et al., design starts with the rationalization phase in which the various components of the system being designed are described. In informing, the rationalization space and describing the design space an adapted version of a Questions, Options and Criteria method can be used. The rationalization phase is followed by a structure space that describes the various components and their links and the activity space in which 3D models (i.e., visualizations) of the system being designed are developed. The 3D models are transferred into the Unity game engine web player, supporting integration, and enabling intuitive manipulation of different objects in the activity space. In addition to these spaces, an instant messaging functionality and a structured evaluation space were added to support the design team and the holistic handling of development work.

Boy et al. (G. Boy et al., 2016) demonstrate the ideas of ADD and the DCs with the I2S-LWR (Integral Inherently Safe Light Water Reactor) project. The challenge related to the design of the reactor was how to incrementally synthesize and integrate the ideas and viewpoints of the 35-member design team and create a common frame of reference as well as gain user feedback on the design. To aid this, a support system called SCORE was introduced in the development process. According to Boy et al. (G. Boy et al., 2016) the I2S-LWR project team made active use of the SCORE design cards documentation to collaboratively generate, modify, refine, and validate both the physical and figurative tangibility of the system. In addition, exploiting the modeling and simulation capabilities of the I2S-LWR SCORE design cards enabled the designers to involve future users (e.g., operators) to evaluate different functions very early in the design. As a main learning from the design of life-critical systems and this particular reactor project, Boy et al. state that support for knowledge management and collaborative work is the major issue. There needs to be a clear understanding between the design team members to reach the best design in the end, and in this the DCs are a central mediating tool. By developing, assessing, and validating DCs within a development process, they can converge toward both good design solutions and appropriate documentation of the design process and solution resulting from that.

Österman et al. (Österman et al., 2016) carried out a study in the maritime domain to investigate the potential of using different 3D representations in a participatory design to elicit design feedback from users. For the study, 18 cadets from the maritime academy were recruited. The authors were also interested in understanding if representative users (i.e., not direct end users) may provide useful and relevant design feedback, as in ship design real seafarers may often be difficult to involve. Scenario-based workshops were organized, and the

representative users were invited to explore four different representational models (2D drawing, 3D models of 1:1 scale, 1:16 scale and CAD model) of a ship bridge. The users evaluated the models both individually through answering a questionnaire and by participating in a focus group. The users ranked the models on a variety of aspects such as easiest to interact with, most convincing, easiest to discuss, easiest to consider alternative solutions, easiest to modify and works best in practice. In the focus group, discussions about the abovementioned aspects were continued and three different scenarios (i.e., mooring, busy fairway, and maneuvering situations) were used for facilitating the model investigations. The analysis revealed that five specific types of user feedback could be obtained through the models: detailed design feedback, design change suggestions, comments related to movement and space, evaluative comments related to body dimensions, and evaluative comments based on tasks, experiences, and alternative scenarios. Detailed design feedback was received most (both from individual questionnaire answers and from focus group discussions), evaluative comments based on task, experiences, and alternative scenarios second most (also from both individual and focus group discussions) and comments related to the bodily dimensions least. The most preferred type of model was the 1:1 model of the ship bridge, with the 1:16 being the second preferred, the CAD the third and the 2D drawing the least preferred.

According to the authors, the study confirms that based on task scenarios and model representations, representative users can provide not only useful feedback on design parameters, but also experiential reflections on the consequences of the proposed design solution and alternative use situations that may pose additional user requirements for the design. In addition, the results show that combining task scenario descriptions with 3D models as mediating and discussion-stimulating artifacts is a successful way for designers to make dialogue happen in a group of users. Even though only representative users were involved in this imaginative ship-bridge design study, the authors suggest that the type of evaluation methods and representations used may also be useful and relevant in a real ship design process and argue that this approach could be even more effective if experienced seafarers were to be involved in the design.

Another study conducted in the maritime domain by Hjelseth et al. (Hjelseth et al., 2015) covers several case studies on the use of real-time 3D game engine-enriched scenarios as a design tool in the participatory design process. According to the authors, one of the main challenges in safety-critical operation is to holistically understand the needs and actions of users and use practices in terms of both contexts and systems. They see this as a problem especially in the early phases of design, at which point there may not as yet be any materialized designs to work with and assist in design specifications.

Game engines are a generation of tools originally introduced in the entertainment context (production of games for platforms like PlayStation). However, the authors suggest that they are also useful for industrial and scientific needs and explore their potential in the context of maritime product development to facilitate expert user involvement. Specifically, they introduced three case studies in which real-time 3D game engine-enriched scenarios were utilized. The

first case study context was crisis management in which the effect of future increased traffic patterns in Oslo Fjord was explored with the aim of identifying potential risk scenarios that should be paid attention to in the design of the system. In the second case study, a safety-critical task of dynamic positioning of a supply vessel in the offshore (i.e., polar) context was studied with a particular emphasis on decision-making in ship navigation. The main aim was to obtain feedback on the interface and to support ship bridge concept design. The third case study focused on the design of lighting systems for offshore helidecks (i.e., landing platform for helicopters) and involved expert users in several design sessions to study lighting design through helicopter-landing scenarios.

The authors used and explored the game engine as a design tool in collaborative design sessions. With the game engine, they aimed to facilitate a collective and shared understanding between the design parties as well as feed collective creativity through enabling agile design iterations. The expert users in the design sessions included, for example, vessel captains, vessel traffic operators and pilots, as well as helicopter pilots and passengers. Some of the design sessions had a larger number of participants, whereas some of the sessions were only held between the designers and one expert user. The authors conclude that the main difference between the game engine-enriched and the other scenario-based methods is the ability of game engine-based scenarios to combine several types of media on the same platform, and to apply behaviors to objects and systems that may be simulated in real time and in context. Furthermore, they reported that game engines and simulation allowed them to explore situations and settings in the front-end stages of design processes and enabled subjective situated user participation and feedback on the complex design of maritime applications.

In the petroleum domain, Oggioni et al. (Oggioni et al., 2021) used work simulation and involved users in the participatory design of an Onshore Collaborative Center (OCC) intended to enable integrated operations. According to the authors, the expenses of offshore operations have driven many oil and gas companies to launch initiatives for improving their operational performance and reducing costs. Consequently, requirements for lower offshore staffing and increased sensor-based monitoring and operations through the onshore centers are introduced. Even though the importance of human factors and user participation is generally acknowledged, the authors state that this is not often used to its full potential. Therefore, in the OCC project, one important goal is to provide the users with real, early, and full involvement in making decisions about their work, systems, and organization. Thus, the project aimed to reflect on how the work dimension can be considered in OCC design through a work simulation from a participatory ergonomic perspective.

In the study, work simulation was used as a central method for work-oriented participatory design. In a work simulation, the workers and other relevant stakeholders are the focal point and the work itself is accepted as a criterion for decision-making. According to the authors, the idea of work simulation is not to find a single right solution to the problem; instead, it brings the possibility of

staging and manipulating certain elements in the work system that are considered significant in achieving the goal. In practice, an Ergonomic Work Analysis and three Ergonomics Simulations cycles were performed to support discussions with participants to create design solutions. The users involved were from the existing staffing of the onshore teams, including members of several operational groups (e.g., monitoring and support teams).

Prior to the work simulations, a work analysis and field observations were carried out to understand the work globally, its main tasks, and the interactions between operation teams. The actual work simulation was carried out in three cycles. In the first session, optional OCC layouts were introduced in the form of paper schematic floor plans, and the participants could use pens to make interventions on them while discussing the alternative plans. The goal of the first phase was to select two optional floor plans for further development. The second session was organized in the room space in which the OCC was going to be built. The discussion was facilitated by a board game with a vinyl-printed schematic floor plan on which the participants could write and erase notes, with pieces representing movable workstations. Based on the discussions in the second session, the ergonomist organizing the work simulations prepared a 3D model of the floor plan. In the last simulation session, the 3D plans were used to discuss the OCC layout and act out some typical work situations (e.g., shift change situation) to see how they would occur in the space.

The authors observed that the game board and a virtual model enabled reflection on the OCC layout, as they made it possible to easily explore and test different ideas. For example, in the last session, the operators had suggested arranging the workstations in a new half circle configuration to better support face-to-face meetings, while still allowing everyone to have a view of the video wall. As a conclusion of the participatory design of OCC, the authors argue that without work simulation based mainly on the elements of the activity, in-depth discussion about the work would not have taken place and the design would have focused on technical devices and details of the new OCC construction. Moreover, they claim that bringing together the different points of view was the driving force behind the modification of the OCC floor plan characteristics– that is, the criteria being modified, the specifications adjusted, and the purposes redefined so that the final OCC solution would be acceptable within the group.

One study that is worth of mentioning (even though its main focus is not on user involvement) concerns the meaning of the paper flight strip tool in the air traffic control context by Mackey (Mackay, 2000). In her intensive field study, she concentrates on exploring the role of a single physical artifact, that is, the paper flight strip in air traffic control practice. She also made comparisons between different types of air traffic control centers, for example, how the flight strips were used in small or large control centers. The study was motivated by earlier failed attempts to digitalize the traditionally paper-based system that had been regarded as a safe and effective work practice by air traffic controllers. It is also argued that the paper flight strips provide a certain level of flexibility that is not supported by computer-based HSIs.

In addition, in her initial background interviews, she found that there were fundamental differences in how each interviewed group (i.e., engineering designers, HF experts, sociologists and air traffic controllers by themselves) characterized the day-to-day work of the controllers and, in particular, their use of strips. Therefore, it was essential to understand in more detail the characteristics of the paper flight strips that may contribute to safety and efficiency, but which are not easy to measure or are not articulated in the official guidelines or work procedures. To reveal the hidden factors, she carried out intensive field observation (hundreds of hours) and interviewed air traffic controllers (a team of controllers at the Athis Mons en-route control center in Paris) about their work and in particular the paper flight strips.

The results provided a great deal of insight on the potential reasons behind the earlier unsuccessful designs. For example, paper strips are extremely flexible – as already mentioned above, they take advantage of both controllers' visual and tactile memory – and without doubt form an essential component of today's air traffic control system. Other more silent but important features of the strips emphasized in the study, to mention some, were their support for controllers' sequential checking of each aircraft routine, and the temporal and spatial framework and level of detailed information they offer for traffic management. Furthermore, even though the controllers had some basic rules for how to fill out the strips, the strips allowed individual styles with respect to how much to write and in what detail. The same flexibility enabled the details of the interactions with the strips to be changed to compensate for or adjust to ongoing externally imposed changes (e.g., defects of digital HSIs).

This kind of shaping of interaction with the tool and the tool's features already comes close to what was referred to as meta-design by Fischer and Giaccardi (Fischer & Giaccardi, 2006) or more generally the phenomenon of end-user development. In their follow-up study, Mackay et al. (Mackay et al., 1998), suggest an alternative approach: an augmented reality-based flight strips that Mackay thinks may finally allow digitalization of strips in a form that the controllers would be comfortable with. The reason why Mackay's study was included in this review, even though it is not especially participatory in its nature, is that it makes an important point about acknowledging and understanding the history and role of artifacts that are aimed to be developed (e.g., digitalized or automatized). The insight yielded by the study is the kind of knowledge and experience which expert users could bring into the design.

Tideman et al. (Tideman et al., 2008) introduced a new product design method to better acknowledge the human perspective in design. The design method is demonstrated with a design case of a lane change support system in the context of vehicle automation. In the first phase of the lane change support system design, twelve users were involved in the design. In the first phase, the users participated on two separate occasions; a reflecting session and a verification session. In the first phase, the authors state that the objective was to verify the completeness and correctness of the design environment and enable users to contribute to this by iteratively working toward their personally preferred specification of the environment. In the second phase, forty-eight users were

involved. All design sessions involved one user at a time and in those sessions, a "personal report" specifying individual user backgrounds, design solution specifications and justifications for the preferred designs as well as short descriptions about user behavior during the design sessions were produced.

To search for a compromise between the varying user preferences, the authors organized all design information into a hierarchy-exemplifying user's perspective. In this process, an approach similar to "grounded theory" was utilized. As a result, specifications of the six (lane change support system) assistants were deduced. According to the authors, the hierarchy of information was also successfully used to specify why users would be attracted to every assistant, what they might not like about them, and how this is related to the circumstances under which they use them. The lessons learned from the lane changing design case allowed the authors to conclude that applying the new product design method would most likely be highly suitable and return the investments in projects that aim at developing new and rather complex products, and in which many different stakeholders are involved. According to the authors, the method will be certainly beneficial in the design of products that should be "first time right" such as lane change support systems, where a faulty version might endanger the users' safety and permanently harm the producer's position in the market.

Björgvinsson (Björgvinsson, 2008) views co-design as a prototypical practice that should be explored through an open-ended exploration of possibilities. Furthermore, he argues that when focusing on practice, in situ explorations cannot be avoided. According to the author, they make it possible to study if the proposed design explorations invoke relevant prototypical practices during work. Björnvisson's final argument concerns tools that should be considered as temporary props for various settings rather than ones with a central role and features that define the activity (learning, knowing, and working). Björgvinsson presents a study made in the context of intensive care unit (ICU) work. The participatory design project was initiated to explore how the employees could better be kept updated with relevant new knowledge and if this could be assisted by means of some technology.

Methodologically, the study was ethnographically inspired, including observation of work, expert interviews and collaborative design and development workshops. One method that was used in the initial phase of the study was what the author refers to as metaphor game. The unit's staff was introduced to a game called ICU as a Family, tailored particularly to the ICU environment, which aimed to aid the nurses and nurse's aides to discuss and negotiate how new technology affects cooperation at work and which artifacts they valued in work activity. The game consisted of a game board representing a generic home layout. In the second round of the game, the board was exchanged to represent an ICU department layout. The game pieces then comprised family members and common artifacts such as telephones and newspapers. For every game piece placed on the board, the participants described why they find the piece important, explained the meaning of the location of the piece on the board and then jointly ranked the importance of the piece. According to the author, the nurses pointed

out that the artifacts they valued most highly were those that engender discussions and sustain traditions.

Another game that was played was called ICU as a Garden, which pointed out that patient care situations were like "greenhouses," meaning a rich place for learning and constructing new knowledge that would be valuable for the whole clinic. However, a recognized problem in the unit was that the gained knowledge did not spread well enough in the clinic. According to the author, the initial phase of the study identified several qualities in the ICU practice that could be built upon, such as peer-to-peer learning during work and the need and satisfaction invested in developing new ways of working. The framing in the design exploration was purposely kept as open-ended as possible to create a rich design phase in which joint analysis of practices could be done and the staff would genuinely have a say in how possible future learning practices could be shaped. The project resulted in self-produced videos that supported staff in learning and sharing of knowledge gained through their experience of day-to-day work.

Kusunoki et al. (Kusunoki et al., 2015) provide a description of a study that aimed to involve the medical team members required during trauma resuscitations in the design of an information display to support situation awareness and teamwork of an ad hoc emergency medical team. The study was conducted with emergency medicine clinicians from two regional hospitals' emergency departments. According to the authors, emergency medical situations share several characteristics with other critical healthcare domains such as work in operating theaters or in intensive care units (e.g., multidisciplinary teams); however, the requirements for awareness differ due to ad hoc team formation, collocated nature of teamwork, lack of information technologies, and tighter time constraints in the situation. Both of the medical practices that this study focused on – that is, trauma resuscitation and emergency medical resuscitation – represent very dynamic processes and require highly specialized medical personnel to administer lifesaving treatments. Moreover, each patient entering resuscitation is treated on a case-by-case basis, depending on the severity of the injury, the patient's demographics, and medical history. Thus, there is a need for sharing awareness to support fast-paced activity, dealing with competing priorities and incomplete information.

Today, this critical information is mainly exchanged within the resuscitation team through verbal communication; however, this project aimed to elicit design ideas for information displays to further enhance the medical teams' awareness. A total of 23 participants representing the core team member roles required during trauma resuscitations or medical alerts were involved in design workshops that were carried out in two regional hospitals (i.e., two workshops were held in each hospital). A design technique called PICTIVE (Muller, 1993) was used as a frame for the participatory intervention. The authors selected this technique because it emphasizes participant-generated design prototypes rather than collaborative analysis and planning of workflow. The design workshops were then constructed around five activities that followed each other: a quick survey, then an individual design session, group design, a rapid information ranking exercise and finally an evaluative discussion about the concerns

regarding the design solution. At the beginning of the workshop, the participants were asked to recall a recent patient situation in which they had personally been involved. According to the authors, this helped the participants to start processing the design task through their own professional expertise and work practice.

The participatory design workshops enabled obtaining contextualized examples of awareness needs as well as yielded a better understanding of the concerns that the users had about their work. Moreover, regarding the information displays, specific design solutions were created to address critical user needs. The authors state that instead of just identifying the key information, they were able to elicit details and examples of how clinicians would like to see the information be presented. Overall, they conclude that by designing and consulting with clinicians through participatory design workshops, the authors were able to compare each role's perceptions on awareness, how they would like to receive awareness support in the display wall and identify concrete design strategies to manage and balance between the different user perspectives.

2.5.2 Studies concerning system evaluation with end users

This subsection reports on studies in which the user involvement and design activity was carried out in a lifecycle phase in which the design was evaluated. As there are numerous studies concerning the human factors evaluation phase, in my review I have concentrated on evaluations in which expert users' opinions concerning the new design played a central role and were used as main data for making the assessment.

Studies in which user involvement concentrated on the evaluation were reported by dos Santos et al. (dos Santos et al., 2009), Hwang et al. (Hwang et al., 2009), and Rajala and Väyrynen (Rajala & Väyrynen, 2011).

Dos Santos et al. (dos Santos et al., 2009) report on another study relevant in the context of nuclear installations and design of control room systems. Even though the focus in this study is more on the evaluation than the design of equipment, it was carried out through a participatory ergonomics approach. The specific object of evaluation was the control room interfaces of a research nuclear reactor. Two end-user representatives were invited to participate in the work of the evaluation team. Similarly to the study by dos Santos et al. (dos Santos et al., 2011) introduced earlier, this study began with the formation of a multidisciplinary team and choice of methods and tools. In the first phase of the evaluation, a human factors questionnaire (dos Santos et al., 2009) was utilized. For the purposes of the evaluation study, the questionnaire was slightly modified from the original questionnaire to expand the original five topic areas (i.e., panel layout, panel label, information displays, controls, and alarms) to six with the addition of the working environment. Forty-eight (48) questions regarding the above cited topic areas were included in the questionnaire. All the members of the multidisciplinary evaluation team filled the questionnaire individually. The score of the human factors questionnaire is defined as the value of the conformance scale multiplied by the importance weights. The results of the questionnaire were used as inputs during the scenario design for the evaluation. The

questionnaire revealed that the team considered that alarms involved the highest risk (65%), and the panel labels had the second highest risk (although lower at 20%).

Two scenarios covering a broad spectrum of factors were defined based on the results of the questionnaire (first scenario: reactor start-up and increase in reactor power up; second scenario: start-up and reactor shutdown due to an alarm in the gamma radiation monitoring device). Operator activity analysis was carried out through structured observation of operator performance and interviews in which the selected scenarios were discussed in more detail (Table 1). In the analysis, an adapted version of the operator monitoring model from Mumaw et al. (Mumaw et al., 1995) was used. This model has three major elements: initiating events, operator cognitive functions and resources to enhance the effectiveness of monitoring. In Table 1, a summary of the operator activity analysis regards the two selected scenarios is presented.

Following the analysis of the human factors questionnaire and operator activity, an alarm-panel development project was initiated. A specified set of functional requirements was defined for the new alarm panel design, with users (i.e., the two operators) contributing their knowledge regarding the needs and difficulties related to operation using information from the old alarms. An industrial designer who was part of the design team was responsible for producing the first sketches of the new panel design. The authors argue that the information gathered made it possible to formulate a series of recommendations for the adequacy of CR design, assisting in the safety assessment of nuclear plant operation and justifying the alarm panel modernization. Moreover, the multidisciplinary team – which harnessed operational experience through involving users in the design and evaluation – was seen to support and greatly contribute to the success of the development project, which according to the authors makes the application of participatory ergonomics practices highly relevant and recommendable in the context of nuclear installations and control room system design.

Table 1. A summary of the operator activity analysis regarding the two selected scenarios (dos Santos et al., 2009).

Cognitive functions applied to scenario one and two.

Scenario	Operation modes	Systems modernization		
		Monitoring	Situation assessment	Response implementation
1	Initial verification	■		
	Start-up	■	□	■
	Increase power	■		■
2	Initial verification	■		
	Start-up	■	□	■
	Increase power	■		■
	Reactor shutdown	■		

The gray shading explains that during the scenarios one and two and operations mode which cognitive functions were used.

Hwang (2009) (Hwang et al., 2009) reports on a control room and HSI validation that took place prior to the commercial operation of Fourth Nuclear Power Plant (NPP4). A structured interview study was conducted involving

twenty-five licensed operators through a focus group procedure. As a background for the interview study, observation of training sessions and task analysis were carried out and used to finalize the interview guide. In the actual structured interviews, the operators were divided into two groups; in focus groups, they were asked to discuss the potential latent problems (i.e., human errors) that may arise in the operation of new digital CR and HSI systems. Two rounds of interviews were organized. In the first round of interviews, the aim was to identify and collect problems related to the interfaces. In the second round of interviews, the identified problems were discussed and analyzed in more detail. In addition, a prioritized list of problems (i.e., altogether 14 problems, of which the three most urgent ones were highlighted) and recommendations for design improvements were drafted to support the detailing of the design of new CR and HSI systems. Even though the operators were not involved in the actual design work to a great extent, their expert opinion was clearly utilized as a main source of information to further the design. Through their experiences, operators could identify possible latent problems and come up with suggestions for how to improve the design to reduce the potential risk of future human errors, thereby making the study and the methods used in it relevant for reviewing ways of involving users in safety-critical system design.

Rajala and Väyrynen (Rajala & Väyrynen, 2011) propose a procedure to evaluate the optimum human work system. In the method, a hierarchic objectives tree was constructed and then applied to describing the target of assessment. The main objective of design activities, "optimum human work," was first set out by experts into three hierarchic subobjective levels: (1) physical, (2) cognitive and (3) organizational issues, which were further divided into subobjectives: (1) lifting and momentum, working posture, physical monotone, (2) own knowledge, information processing, own skills, and (3) leadership, data management, participation. These hierarchical levels formed a set of criteria to assess the work system. Interviews with three user groups (entrepreneurs, white-collar workers, and blue-collar workers) were carried out in small and medium-sized metal industry enterprises to define the weight of each criterion in evaluating the system. Altogether 50 workers participated in the study. In the interview procedure, the users were asked to compare each criterion with every other criterion. Thus, all categories were thoroughly considered by the different user groups. The results of the study showed no significant differences between groups of entrepreneurs or white-collar workers. Instead, the blue-collar workers were significantly unanimous – on average, they clearly favored physical issues more in valuing the work system. The group of subobjectives concerning organizational issues was most important. However, cognitive issues were weighted as being almost as important. Contrary to previous studies carried out in developing countries, the blue-collar workers (in the developed country context) also assigned the least weight to physical issues. The authors suggest that the design method used is participative design because it combines researchers and interviewed workers. The method definitely utilized users' expert opinions to value the different dimensions in the work system. However, the study did not aim to produce any specific new design; instead, it may have been described

as a background study to develop a user-informed evaluation framework or produce valuable user feedback for generally developing the work systems regards their different qualities (e.g., health and well-being, safety, and performance).

A healthcare-related study that concerned the Northern Norwegian health region's endeavors to modernize its information systems and thus improve its health services was reported by Johannessen et al. (Johannessen & Ellingsen, 2008). The study concentrated on an information system that was developed for handling laboratory requisitions between the hospital laboratories and general practitioners. It was found that paper-based laboratory requisitions from primary care often contained errors or lacked some clinical information and detail. This observation led to the establishment of a new development project in collaboration with a company called Well Diagnostics and the University Hospital of North Norway (UNN). According to the authors, the aim was to design and implement a system to improve the work and information flow between primary care and hospital laboratories, and to integrate this into the existing information systems on both sides, hence increasing quality and reducing workload.

The central methods used in the project were the agile software development approach (in three-week development cycles) and involving the user perspective by means of participatory design. In addition, in the challenge of enabling information system integration between the different stakeholders' systems in the agile software development process, the user role is considered clearly defined, which in the case of this complex organizational setting it was not. The new laboratory requisition system was intended to cross organizational boundaries and mediate between the different users in hospitals, leading to a situation in which the traditionally clearly defined user role becomes increasingly blurred and heterogeneous. In the project, the Well Diagnostics developers wrote, and prioritized user stories based on the customer feedback and used those as a backbone for developing the functionalities of the system. According to the philosophy of the agile development approach, the first version of the system to be designed is often drafted very quickly and includes only very basic functionalities. Then, through the iterations, these functionalities are further refined, and new functionalities are introduced according to the scheduled release plan for different user stories. To gain regular user feedback and evaluate the system with relevant user groups, a pilot channel was launched – a new version of the system is rolled out to pilot users for testing at three-week intervals. After the pilot users have tested the new functionalities, they are directly uploaded to the other users and a new development iteration cycle is started. However, in the process of developing the new laboratory requisition system, the authors have also witnessed many challenges faced in involving users as the complexity of the system increases (e.g., new functionalities are requested), the size of the system escalates (e.g., new hospitals start using the system) and the number of users (e.g., new users are discovered, such as receptionists in general practices) and systems to integrate increases. In their conclusions, the authors emphasize the

need to develop the methods for user involvement in agile software development projects as well as the position and responsibilities of vendors in this process.

2.5.3 Studies concerning design in use

A design technique called meta-design is promoted particularly in the context of software development and IT systems. Meta-design refers to a design approach that enables and supports humans in shaping their socio-technical environments (Fischer & Giaccardi, 2006; Giaccardi, 2005). In a work context, this approach empowers users to adapt their tools to their needs. The idea behind meta-design is that systems are constantly evolving, and it is impossible to anticipate all user needs beforehand. That is why users should be able to reshape and adapt systems so that they are a better fit with their needs and working practices.

In the healthcare domain and design of medical equipment, there have been many studies that aim to involve users in design when the system has already been implemented and is in use. Mogensen et al. (Mogensen & Wollsen, 2014) reported a study in which they aimed at participatory design in the realization phase of an IT development project within a large-scale, complex, and commercial context. With "realization," the authors refer to the phase that may often be seen as an end point of most participatory design projects, that is, the phase that focuses on the successful implementation of the envisioned changes and future solutions. The empirical case focused on the pre-hospital sector and the development of a national IT solution for this activity. According to the authors, the new system was intended to improve and enable new forms of documentation, coordination, and communication within and between acute medical coordination (AMC), alarm centrals, ambulance personnel (medics and paramedics), emergency departments at hospitals, and many other parties, such as police and fire services. The authors' role in the project was to facilitate "adaptation" and "user involvement," and to this end they applied a participatory design process. In specific, by means of constructive realization and adaptation workshops, several user groups were invited to discuss how the new system would change their future practice. According to the authors, a point of departure for exploring these changes and unfolding future activities was found from the concepts of Communities of Practice, Legitimate Peripheral Participation, and Boundary Objects. In addition, in the workshops, a wide range of HCD techniques were used, such as incident games, prototyping with mock-ups, case stories, prototype evaluations, group discussions, plenary discussions and generating principles for technical design and future practices. The total participant group exceeds 60 persons, including participants representing diverse pre-hospital functions such as nurses and doctors from emergency departments, acute medical coordination staff and managers from different levels of the organizations. The authors conclude that despite the somewhat fixed starting point (i.e., requirements and use cases were already specified), participatory design had much to offer ¬– that is, a host of insights, objectives, tools, and techniques from typical participatory design may also apply well in a large-scale complex context and

later phase of design (i.e., realization phase). Moreover, by addressing and actively using complex issues related to pre-hospital practice, the authors report that they are able to keep the bigger picture in mind and thereby increase the possibility of successfully realizing the system.

Another study reported by Silsand et al. (Silsand & Christensen, 2012) was done in connection with the development of a new large-scale Electronic Patient Record (EPR) system for North Norwegian hospitals. The vendor (i.e., DIPS ASA) of the EPR system aimed to offer a modular system to enable users to build their own EPR software and user interface. This tailoring functionality would make it possible for the new EPR to better respond to the everyday work practices and specific needs of the local hospitals. However, as the authors note, such a "do-it-yourself" approach calls for an "empowered user" of a type not commonly found in the operation of large information systems in hospitals. According to the authors, the target configurability of the software is not straightforward, as it is not obvious who will decide what the final design should look like, how much tailoring should be possible and in which situations. To further specify the new EPR functionality, a user-oriented LEAN methodology was applied. In the project, several workshops with users and the vendor were organized, involving clinicians from different health professions and from 11 different hospitals. The authors report that the workshop participants created user stories that point at obstacles that have been identified in everyday work practice and which could possibly be solved with a proper ICT tool. For example, one specific context in which the advantages of a new EPR system and the tailoring needs were identified and discussed was the development of a surgery planning tool. Surgery planning-related user stories were used in developing the new tailored functionality. One aim of the practice-oriented LEAN methodology and user involvement was to make the users – that is to say, the local hospitals – better equipped for the task of shaping the EPR to better suit their specific needs. Neither the organization of workshops nor the use of user stories are described in detail, but it seems that some positive developments and engagement in the design was reached by means of active user participation.

End-user development means that users are actively involved in software development. Costabile et al. (Costabile et al., 2005, 2006) have promoted a method called the Software Shaping Workshop (SSW), which is a virtual workshop (a kind of digital platform) where different design parties including expert users can shape the software functionalities. According to the Costabile et al., the users are the actual owners of problems who also hold a domain-oriented view but often lack technical programming skills, which is why it is especially important to support their participation in developing domain-specific software applications. In SSW methodology, the word "workshop" is understood as defined in the Merriam-Webster Dictionary, that is, "a small establishment where manufacturing or handicrafts are carried on," which differs slightly from what is meant with workshop, for example, in the Future Workshop technique by Greenbaun and Kyng (Greenbaum & Kyng, 1991). Costabile et al. demonstrate the SSW methodology in the context of planning a new tool for medical diag-

nostics and consultancy. Analyzing medical examinations and making diagnoses is often a joint activity in which different specializations should give their own contribution according to their expertise. However, because of the demands of busy hospital work, less time is available nowadays for face-to-face meetings in which the clinical cases can be collaboratively analyzed. According to Costabile et al. (Costabile et al., 2006), today's information technology has the potential to overcome this difficulty, and many software environments may support collaboration at a distance. Thus, the aim of the project was to develop a software system that allows expert users (i.e., medical specialists) to analyze the medical cases and to formulate their own diagnosis while considering the opinions of colleagues.

A field study was carried out in which physicians were observed during their daily work and when having consultancy meetings with their colleagues. In addition, several semi-structured interviews were performed to better understand the documents, tools, and languages used in clinical work. Based on this, a first version of the application workshop was created. The system was introduced in use at SSW and the users could now further tailor the diagnosis system according to their specific professional needs (e.g., shape a view enabling neurologists to study EEGs but also in some cases analyze MRI plates versus the neuroradiologists' view which only shows MRI, which is their main interest). Costabile et al. (Costabile et al., 2006) foresee that the SSW will enable the participation of all the stakeholders in the development of the final system, each one from their own perspective, using language familiar to them. The users may now serve in two roles, that is, as a user and as a designer and customize the system according to their needs.

2.6 Discussion on methods for user involvement in safety-critical system design

I will summarize the insights and findings from the related research to identify gaps in knowledge underlying the final research questions of this thesis introduced in subchapter 1.4.

In reviewing the related research, I first sought to identify characterizations of safety-critical systems as an object of human-centered design. Safety-critical systems appear to form an extremely multifaceted problem-space and finding appropriate design solutions often involves a highly networked and multidisciplinary design team. In discussing the design culture and dialogic design, Manzini (Manzini, 2016) calls for recognizing that every design process is co-design, and that the process therefore must provide and allow space for the points of view and active participation of many different actors. This claim may be even more true in the context of safety-critical system design, as no single person can accomplish a design task of that magnitude alone. Thus, creating a shared awareness and common vision among the different design parties may be especially important in the context of safety-critical system design. For example, in a project in the healthcare context described by Garde (Garde & van der Voort, 2010), the participatory design process and the success of the design outcomes

were challenged by an absence of a future vision and limited use and awareness of the knowledge and information available in hospitals. Therefore, the questions of what characteristics of the system and in what form they should be described so that the sought-for future direction and resources for making the change would be tangible to everyone participating in the design are essential in the context of designing safety-critical systems.

Safety-critical systems tend to also be very complex by their nature (G. A. Boy, 2012). Even a single design solution may be restricted in so many ways that it may be difficult to comprehend the causal relations behind the different design decisions related to finding the specific solution. Over the years, the complexity of systems has further increased due to the growing number of integrated systems and user groups as well as the utilization of sophisticated high-tech equipment (e.g., highly automated systems and artificial intelligence-based solutions)(Bratteteig & Verne, 2018; Geudon, 2016; Gyldenkaerne et al., 2020; Johannessen & Ellingsen, 2008). Consequently, it has become even more difficult to see how all the pieces function together and what the potential consequences of design decisions may be. This is true in safety-critical context as well, where the design task easily becomes difficult to handle alone and overwhelming even for those who carry out HSI design daily, not to mention the expert users whose core task is elsewhere and operative by its nature. As Costabile et al. (Costabile et al., 2005) note, the expert users are still the actual owners of problems, but they often lack the technical design skills they would need to capitalize on their strong domain-oriented view and first-hand operative experience when engaging in design work. Thus, supporting the expert users' participation in developing their work and tools is especially important.

The gap between the users' world and the designers' world has been also discussed by researchers such as Muller (Muller & Druin, 2003). In the context of safety-critical systems, the design organization and the operative organization are in many cases quite distant from each other. For example, it is common that a vendor – instead of the organization operating the safety-critical system – carries out the design work, which further complicates the integration of operative experiences into the design process. Thus, even though not being the particular focus of this thesis, the communication between the vendor and the operating organization as well as the traditionally neutral vendor role should be critically examined so that the end users' needs and preferences can be better met in the design process (Garde & van der Voort, 2010; Johannessen & Ellingsen, 2008). It is also essential to provide support for the tracking of design changes in terms of chronology as well as carefully documenting and obtaining well-informed overall status of design (G. Boy et al., 2016; G. A. Boy, 1997b), as shared understanding constitute a starting point for any collaborative design activity. Both the designers and expert users are without a doubt highly specialized professionals when it comes to the safety-critical systems they are involved in; however, they view these systems from very different points of view. Consequently, the starting point for participatory processes and finding a common language and grounds seems challenging.

Human centered view and human factors studies within safety-critical system design have a long tradition. Many times, incidents or accidents partially caused by human related issues have highlighted the need for organizations operating safety-critical systems to develop their HF processes. However, the human factors work in organizations that operate safety-critical systems seems to be somewhat analysis and evaluation-oriented (Boring et al., 2015a; Boring & Lau, 2015; Norros, 2014). Safety-critical organizations are often rather conservative in their approach to applying new technological innovations, and continuously monitor and analyze the risks that the introduction of these technologies and work processes may involve.

There are organizational functions that take care of analyzing incidents that have occurred and carry out safety reviews, for example, the work of Operation Experience groups in the context of NPPs. However, the design efforts following from these analyses are often incremental and the focus is on the details. Moreover, when new HSI systems are introduced, HF experts may evaluate if the systems are acceptable from the usage point of view, and if there are any special aspects to be considered, for example from the training point of view. These evaluations are more summative by their nature. There is far less research reporting on HF work that focuses on innovative aspects of designing safety-critical systems. Another issue is the question of independence, which is always present in the design and evaluation of safety-critical systems; that is to say, in the safety-critical context, it is not acceptable for designers to evaluate their own designs. Consequently, the HF has needed to take their possessions and the methods and processes on how to participate and contribute to making innovations and design (e.g., conduct mode formative type of evaluations) have in practice been underdeveloped.

Still, for example according to Nureg (USNRC, 2012), human-centered design is an essential part of HFE practice in the nuclear domain. The four general principles of HCD are (ISO_9241-210, 2010): 1) actively involve users and create user and task understanding, 2) allow an appropriate function allocation between the user and the technology, 3) conduct iterative and 4) multi-disciplinary design. These principles aim at designing products in cooperation with the potential users so that the final designs would better match their needs and preferences. However, in the NPP domain (maybe also in safety-critical domains generally), it seems that the first principle, that is, involve users is applied least often, whereas the iterative design principle (i.e., gradual iterative refinement of the design solution), for example, seems to have been far more well adopted.

It seems that the literature generally lacks descriptive detail of the activities carried out within the safety-critical design process – and perhaps even less attention is paid to activities related to involving expert users. The same applies to reporting on how successful or unsuccessful these participatory activities have been (e.g., cost effectiveness). Consequently, with some exceptions, little is said in the literature about the participatory design methods that are specific to safety-critical system design. Table 2 provides a summary of the participatory methods used for involving users in safety-critical system design. In Table 2, in addition to the lifecycle phase (i.e., early, evaluation and in use phases) in which

the users were involved, the domain, the tools and methods, the participants and the outcomes of the design projects are summarized.

Table 2. A summary of the studies on participatory design and user involvement in safety-critical system design.

	Domain	Tools and methods	Participants	Outcome
Early design phase	NPP (dos Santos et al., 2011)	Simulated tasks (interviews, talk-through) and collaborative function analysis by design team	Licensed operators (2)	Reference equipment analysis (information needs), characterization of the working environment
	NPP (G. Boy et al., 2016)	SCORE Design Cards, including rationalization, structure, and activity spaces	35-member design team; the number of end users involved was not mentioned	Comprehensive design documentation/rationale that links visually tangible objects to their abstract descriptions
	Maritime (Österman et al., 2016)	Scenario walk-through of representational models	Maritime Academy cadets (18)	User feedback (design feedback and change suggestions, space and anthropometry feedback)
	Maritime (Hjelseth et al., 2015)	3D game engine-enriched scenarios	Vessel captains, traffic operators and pilots, helicopter pilots and passengers (around 18)	User feedback (potential risk scenarios, UI design feedback), shared understanding between design parties
	Petroleum (Oggioni et al., 2021)	Work simulation in three cycles with paper schematic drawings, game board and 3D models/visualizations as material means	Existing staffing of OCC teams, the number of end users involved was not mentioned	Design solution (i.e., a new OCC floor plan)
	Flight control (Mackay, 2000)	Simulated recall (collaborative viewing of video recordings of work)	Air traffic controllers and air traffic controller students (11)	Documentation of operating experience and work practices as a basis of design
	Vehicle autom. (Tideman et al., 2008)	Virtual reality models, game engine and scenarios	Car drivers (60)	Feedback on design environments' completeness, design solutions
	Healthcare (ICU) (Björgvinsson, 2008)	Ethnographic field study (observation of work, interviews), design workshops (metaphor game), prototyping	ICU physicians, anesthesiologists, critical care nurses, nurse's aides, physiotherapists and social workers (around 124)	Ideas for tools to support knowledge development, concepts, and prototypes (self-produced videos for knowledge sharing)
	Healthcare (emergency teamwork) (Kusunoki et al., 2015)	Design workshops, PICTIVE (Muller, 1993), survey, individual and group prototyping (low-tech design objects, e.g., paper and pen), priority ranking and evaluation	Clinicians (the core team member roles required during trauma resuscitations) (23)	Critical information needs, design solution/s (information display)
Evaluation	NPP (dos Santos et al., 2009)	Prototype evaluation	Licensed operators (2)	Usability problems
	NPP (dos Santos et al., 2008)	Functional testing in real environment	Licensed operators (2)	Usability problems, specific procedure design needs
	NPP (dos Santos et al., 2009)	Questionnaire (expert opinion), scenarios, prototyping	Licensed operators (2)	Design solution (alarm panel HSI)
	NPP (Hwang et al., 2009)	Focus group (structured interview, expert opinion)	Licensed operators (25)	Latent problems (scored for their priority, design suggestions)
	Metal industry (Rajala & Väyrynen, 2011)	Interviews (based on a hierarchic objectives tree, expert opinion)	Entrepreneurs, white-collar and blue-collar workers (50)	Dimensions of work system (scored for their value for different user groups)
	Healthcare (laboratory) (Johannessen & Ellingsen, 2008)	Agile software development through design iterations in three-week cycles (prioritized user stories), and evaluation	Physicians and laboratory personnel (initial phase 26, the other two phases the exact number of	Product (IT system), user feedback

		through a pilot channel with pilot users	users was not mentioned)	
In use/ operation	Healthcare (pre-hospital sector) (Mogensen & Wollsen, 2014)	Adaptation workshops, focus groups, plenary discussions, scenarios (incident games), prototyping (mock-ups) and evaluation	Diverse pre-hospital groups (over 60 participants)	Principles, common understanding of system and practices, bigger picture
	Healthcare (Elect. Patient Record) (Silsand & Christensen, 2012)	User-oriented Lean methodology, workshops (user stories)	Clinicians from 11 hospitals (around 100)	Products (e.g., surgery planning tool), hospital personnel better equipped to shape and tailor EPR
	Healthcare (medical diagnosis tool) (Costabile et al., 2006)	Software Shaping Workshop (SSW), interviews, scenario design, prototyping.	Radiologists and pneumologists. neurologists and neuroradiologists (the exact number of users is not mentioned)	Application-specific SSW, software system tailored to user needs.

Many of the methods that were used in safety-critical system design to involve expert users relied on mock-ups and prototypes to make the solutions tangible and to elicit users' experiences on the new designs (Healey et al., 2013; Koskinen et al., 2013b; Lu et al., 2007). The evaluation of mock-ups and prototypes was often also enriched with some scenario descriptions (i.e., series of hypothetical actions and events) or simulations emulating the key characteristics of that specific operating environment, thereby helping the users to experience the different functionalities of the proposed design solution (Hjelseth et al., 2015; Oggioni et al., 2021; Tideman et al., 2008). Another used method was applying different kinds of individual channels such as questionnaires and feedback reporting systems through which the expert users could express their opinions and concerns (dos Santos et al., 2009; Johannessen & Ellingsen, 2008). Most commonly, the users were involved in design through group activities such as focus group discussions or future workshops (Hwang et al., 2009; Mogensen & Wollsen, 2014).

The methodologies for involving expert users in safety-critical system design should be contextual and they should be able to address the particularities of that specific work environment and the critical tasks that the new solutions are designed for. Thus, a more thorough analysis of the work activity and the work context should be obtained as a basis for new designs. Most of the prevailing methods for involving users focus on handling the concrete materializations of design ideas (e.g., variety of mock-ups and prototypes), but they rarely try to connect or analyze the solutions in contexts broader than the specific work sets. However, the methodological discussions on how to describe and form a model that captures more than the immediate interface level of new HSI designs is limited in the literature. Creating different kinds of conceptual and functional models could potentially provide one means of engaging in a more profound discussion with expert users about the new designs. In addition, for example, UX goals have been introduced to communicate to the designers the meanings that the new tools may have in peoples' working lives (Kaasinen et al., 2015). Yet, the literature lacks descriptions of methods that would allow expert users to participate in the analysis and reflection of their work at a deeper level and in an early phase of design when the initial requirements are set and when no actual design solution necessarily exists. It is evident that participatory methods

that would allow viewing the new design solution (e.g., new work tool) as a part of the wider socio-technical use context would provide a more adequate design basis for safety-critical system design than the current methods allow (Fogli & Guida, 2013). A broader perspective would also allow more grounded discussion on the potential influences of different design decisions, that is, how the work practice may develop or change in more general terms if the design solution would be implemented and taken into use (J. Simonsen & Hertzum, 2012b). Thus, safety-critical system design would benefit from methods that would facilitate discussion that may reach the more abstract and conceptual level of designing as well as allow drawing on the full capacity and richness of experts' user experiences (Grundgeiger et al., 2019; Savioja et al., 2014).

Moreover, the used methodologies reported in the literature, are somewhat passive from the user involvement point of view, as the expert users are merely invited to review and evaluate the resulting design solution together with the designers. Clearly, the methods do not address the full potential and professional capacity of the expert users to discuss their tools and work practices. As currently applied the user centered methods within safety-critical system design falls short of what HCD and especially user-involving participatory processes can be about: a process of mutual learning and creating together. At best, these methods should involve expert users in contributing to design with their experiences and knowledge and generating ideas and future directions for their work. Having users participate as test subjects in evaluations in later phases of the development is simply not sufficient for reaching the keynote of human centeredness. The grounding idea of participatory design is to allow a confrontation between different types of knowledge (Oggioni et al., 2021) and through a mutual learning process reach an agreement about the design solution and future direction.

As a summary, in review of related research, several research gaps regarding the expert user involvement in safety critical system design were identified. Even though the literature lacks descriptive details on how expert users are involved in design, it become obvious that most often the interaction with the expert users take place around concrete design artefacts (i.e., mock-ups and prototypes) whereas the overall concept and how it may influence work activity as whole was rarely explored with the experts. Only few examples were found on how to make design solutions tangible in more conceptual level. Yet, it was reported that the lack of common vision frequently prevented developing the systems as the design participants had varying ideas about the content of the solution and the future direction. Another issue that come across was the strong emphasis on evaluation instead of the innovative aspects of developing safety-critical systems. Expert users were invited to evaluate the design solution often later phases of design when many of the founding design decisions had already been taken. Consequently, demonstrating ineffectiveness on what comes to the utilization of expert users' operative knowledge in design. Clearly there is a need to claim a stronger design orientation in involving users in safety-critical system design and give the expert users a more active role from the beginning of the design process when the solutions are still discussed in more abstract terms.

From these gaps in research appear also the justification for the main research question of this thesis, that is, how can participatory methods for expert user reflection on work – including both exploring and evaluating individual task demands and future development prospects – be furthered to better integrate human and social considerations in safety-critical system design?

3. Empirical cases

In this chapter, a description of the research work carried out to complete the thesis is provided.

The following subchapters present studies that all describe safety-critical system design. Three of the studies included in this thesis are related to the NPP context. However, the specific application areas in each of the studies set very different design demands, as one concerns normal operation and another outage operation, while the third is a retrospective review of participatory design case. The other three papers introduce design studies on safety-critical operations in domains outside the nuclear field. One introduces a pesticide-spraying support system development in the context of food production and farming. Another non-nuclear study concerns process control activity more generally, including the operation of other types of processes as well (e.g., conventional power plants). The last study focuses on an entirely different field of safety-critical activity, namely the design of automated transportation.

3.1 Initial studies

At the turn of the millennium, there was a great deal of interest among both researchers and industry in studying the possibilities of new advanced technologies. At that time, interactive touch screen technologies were just being introduced into a number of consumer products. It seemed possible that technology would embed everywhere in our surroundings and enable people to adopt new ways of interacting with their environment. Consequently, many academic research proposals concerning future technologies emerged.

VTT had its own initiatives as well, one of which was a project called Novel Affordances of Smart Environments (NASE project). The aim of this project was to study and better understand the possibilities afforded by advanced technologies in both our everyday home and work environments. One central technology that was studied in the project was multitouch technology and how it could potentially benefit industrial process control activity, for example, by allowing

more direct interaction and operation of the system. One of the first research contributions in the NASE project was a literature study concerning the concept of affordance and new emerging technologies. The project also organized an international workshop with several invited speakers. One important insight of these research activities was a methodical problem related to studying the potential of concept-level ideas when the affordances become actualized and real later when interacting with the environment. Thus, using the concept of affordance in design does not seem to be that straightforward. Nevertheless, further investigations on the concept highlighted the importance of understanding users and the content (e.g., preferences and UXs) of their goal-oriented activity in an environment. Involving the users in exploring and designing their future work environments seemed necessary to achieve successful design outcomes. Another important learning from these studies was that it would be necessary to take a wider view (i.e., the broader context of technology usage) instead of just focusing on the individual task level of using tools.

Following the literature study and initial analysis, two case studies were organized. One of these concentrated on smart home applications and the other on industrial process control activity. Within the industrial case study, an explorative user study was set up to investigate the use of interactive multitouch displays in monitoring and controlling processes (Table 3). Paper 1 reports the results of this explorative user study. One central question posed at the beginning of the study was how users could be helped to see and explore the potential of a technology that is still not very mature and for which a domain-specific functioning prototype could not be built cost efficiently for early trials. The focus was on users (instead of the technology) enabling them to explore the potential and gain early experiences on how it would be to interact with the environment in a new way using touch-based interaction.

The explorative user study was conducted at the VTT research premises. Altogether 10 participants were recruited for the study. The technical setup for the study was purposely realized with a very low-fidelity and low-cost display mock-up. In practice, the display mock-up for the study was constructed from a 97 cm x 58 cm Plexiglas plate that was placed on a movable stand specially designed for fitting large-screen displays. The actual user test was comprised of three different kinds of tasks. In the first set of tasks (24 individual tasks), the user associations on different hand movements were inquired by asking them to perform simple operations on the display, such as zooming in and out or opening a file. In the second set of tasks (31 individual tasks), the users were instructed to interact with the display in a predefined way, for example, touching the display simultaneously with one finger from both hands with a long, light, and precise touch. After this the users were asked to evaluate the interaction in terms of four aspects: 1) how comfortable the interaction felt, 2) how easy the interaction felt, 3) how accurate the interaction felt and 4) if the users had associated the specific hand movements with any particular operation. In the last set of tasks, the users were given pieces of paper of different shapes and sizes and they were asked to interact with them in a specific manner; for example, the users were asked to rotate three different sizes of circles (both clockwise and counterclockwise). The

user interaction was video recorded with two cameras, one capturing an overview and one capturing a close-up view from top down to the display surface. At the beginning of each test session, short background interviews were conducted to collect participants' demographic information.

This explorative user study showed that it was possible to investigate users' associations and preferences on touch-screen interaction early on with the help of very low-fidelity mock-ups, much in advance of any functioning prototypes being built. However, the participants of this study did not represent any specific group of expert users or domain, and the tasks were not related to any specific industrial operations, and thus it is expected that the results may tell more about the general preferences that people have with regard to touch-screen interaction than how promising the technology would be in an industrial process control activity. Nevertheless, the insights may still be valuable when designing safety-critical touch-screen applications in which usability and error-free operation is of importance. However, it would be necessary to develop new ways of involving users in designing and exploring solutions early on, ones which would be contextual and enable users to reflect on the specific work tasks for which they are responsible.

Table 3. Summary of research study in Paper 1 summary of the studies on participatory design and user involvement in safety-critical system design.

	Domain	**Methods**	**Participants**	**Year**
Research study	Process control activity in general	Experimental prototyping of hand gestures with Plexiglas, interview, questionnaire	Engineers (10)	2008
Research question	Sub-question 3: What kinds of contributions can expert users deliver for safety-critical systems design in different phases of the product lifecycle?			
Paper	Paper 1: Koskinen, Hanna; Laarni, Jari; Honkamaa, Petri. (2008) Hands-on the process control: users' preferences and associations on hand movements. In CHI '08 Human Factors in Computing Systems Extended Abstracts, April 5-10, 2008, Florence, Italy.			

Another user study on interactive large-screen displays was conducted within the OECD Halden Reactor Project (Table 4). The specific application area for the interactive displays was outage control centers (OCC) (Koskinen & Hurlen, 2011). In NPPs, outages are organized every year to carry out the needed maintenance works and replacement of equipment. During an average outage, 10,000 to 14,000 individual work tasks are carried out, and thus planning, managing, and coordinating the outage is a major effort that demands its own organization. The OCC functions as a kind of nerve center of the outage operation, from which the progress of the different activities is supervised and managed. The aim of the research study was to explore and investigate the potential of interactive displays in OCC operation, such as whether such displays could support collaboration and teamwork in problem-solving situations.

First, a literature review on interactive touch-screen displays was carried out, after which two in-depth interviews with experienced outage operators were conducted to better understand outage operation and to elicit the user requirements for developing the tabletop display concept. In the concept design phase, different prototyping techniques were used for exploring the design ideas further. Within the project, an evaluation workshop was organized in which a video

prototype (based on non-functioning user interface mock-ups) of the outage display concept was used to elicit user feedback from the outage operators.

The results of this user study are described in Paper 2. Compared to the study discussed in Paper 1, the OCC study is situated further in the design process, being clearly a concept design project in which the demands of the work domain are modeled, and design solutions based on those requirements are proposed. The study was future-oriented and explorative by its nature and the design solution was mainly captured in the form of mock-ups and prototypes in different stages of maturity. Consequently, documenting the user requirements, the design rationale and the related human factors data in a way that would fulfill the demands set for the development of the safety-critical systems was not considered central in the project. However, the project initiated the first attempts and suggestions on how to present the work activity, its demands and the emerging design solution together and then constructively discuss them with the users.

Table 4. Summary of research study in Paper 2

	Domain	Methods	Participants	Year
Research study	NPP, outage	Interviews, real outage schedules, design workshops, design explorations with paper mock-ups and video prototype	Outage personnel: outage director, one-stop shop supervisor, outage manager, outage shift manager, outage shift supervisor, main CR Shift supervisor, scheduler (7)	2010
Research question	Sub-question 2: What kinds of functional models of work should be used as methodological means to facilitate expert-user reflection on work and as a presentation around which constructive discussion between the designers and users can take place early on in the design process? Sub-question 3: What kinds of contributions can expert users deliver for safety-critical systems design in different phases of the product lifecycle?			
Paper	Paper 2: Koskinen, Hanna; Hurlen, Lars. (2011) Outage on the table: the design of interactive surfaces for collaborative operation in outage control centres. In ECCE '11 the European Conference on Cognitive Ergonomics, August 24-26, 2011, Rostock, Germany.			

3.2 Developing functional modeling of Tools-in-Use

In the following research activities within the context of safety-critical system design, we identified possibilities to test and further develop the ideas for how to model and describe the emerging design solution and use this description as a catalyst for the participatory design process and user involvement. One of these research efforts was a joint international research activity (MMOtion project) aiming at defining a European research roadmap for Man-Machine-Organization processes within the nuclear sector. This project analyzed and discussed the current and future situation of many of the topics (i.e., design and evaluation methods, human-system interaction) that are closely related to this thesis. Within the demonstrator work package of the MMOtion project, we developed the first functional Tools-in-Use model that aimed at capturing the content and design rationale of an innovative human-system interface called FITNESS (Functional Integrated Treatments for Novative Ecological Support System). A European research project called SmartAgriFood provided us with another opportunity to test our modeling approach in interacting with expert users in the context of food production and pesticide spraying. In the project, the functional

modeling approach was applied systematically throughout the whole design process.

Conducting the studies provided opportunities to reflect in practice on the theoretical underpinnings of the modeling approach and its use in participatory design activities within the human-centered design process. The modeling approach was initially outlined in a chapter (Paper 3) describing the evaluation of FITNESS HSI that was included in the Core-Task Design book (Norros et al., 2015). The results of systematic use of the modeling approach in user involvement in the pesticide spraying case context are reported in Paper 4, which was published in Interaction Design and Architecture(s) Journal.

3.2.1 Evaluation of an innovative human-system interface for NPP

The evaluation of the FITNESS concept was conducted within the MMOtion project's demonstration work package (Table 5). The general topic of the demonstration work package was to pilot a human-factors evaluation method for an innovative technical concept. The innovative technical concept that was selected to be the focus of the evaluation was the FITNESS system, which is a simulator platform incorporating a computerized human–system interface concept developed by Électricité de France (EDF). Even though the FITNESS system has a fully functional interface that can be used to operate the simulated 1300 MW PWR process, FITNESS has never been implemented in real use and in the NPP context; it represents a very different type of HSI than what is conventionally used to operate the NPP process. Thus, it is an innovative design concept and by no means even close to a finalized product. The human-factors evaluation methodology that FITNESS was aimed to be tested with was an evaluation approach called Systems Usability Case (SUC) (Koskinen, Laarni, et al., 2021). The SUC approach is based on safety case thinking and the notion of systems usability (Savioja, 2014), and it relies on the design requirements as central criteria for evaluation. Therefore, it is essential to understand and carefully analyze the design rationale and the details of the design concept. The results of the analysis of the FITNESS system's design documentation were summarized in the form of one of the first Tools-in-Use models.

To demonstrate the SUC evaluation approach and to test the promise of the FITNESS HSI concept, an empirical user study was conducted at the EDF SEPTEN site in April 2010. Altogether four licensed NPP operators (two Finnish operators and two French operators) participated in a three-day evaluation session. On the first day, the operators received training for using the FITNESS system, after which on the second day five separate scenario runs were conducted with the operators. On the third and final day, a focus group discussion was organized to discuss how the operators had experienced the FITNESS system. The data collection efforts were quite extensive: At the beginning of the evaluation session, short individual interviews were conducted with each operator to collect the participants' background information. The training session was video, and audio recorded to collect the first impressions of the operators concerning the FITNESS system. The actual simulator runs were video-recorded with overview and head-mounted cameras and task load information was

gathered after each scenario run following short process tracing interviews with a predefined set of questions about the specific FITNESS design solutions. In the process tracing, the video recordings from the head-mounted cameras were used to facilitate the discussions. The focus-group discussion on the last day was organized in the simulator to make it easy for the operators to refer to the different features of the FITNESS system. The focus-group discussion was also recorded.

The human-factors evaluations of human-system interface concepts should serve an innovative function and seek design feedback for improving and directing the further development of the design solution. In the early stages of the design process, the evaluations should help in answering the question of the development potential of the proposed design solutions. It should also be possible to differentiate between the promise of conceptual level design decisions and the success of their materializations as interfaces. According to the notion of systems usability (Savioja, 2014a), in addition to the performance measures, the way of acting and the user experience may be used as indicators when considering the appropriateness of tools. At the concept design phase, the experiences and reflections of expert users may be more valuable in foreseeing the promise of the design solution when many traditional human performance measures (e.g., execution time and errors) cannot still be reliably applied in the evaluation of the design. In the case of the FITNESS system, it seemed that some concept-level design solutions were promising, but there were usability issues in how these ideas materialized at the interface level. The functional Tools-in-Use model also made it possible to pose more precise questions concerning the FITNESS system, and constructively discuss the different aspects of the proposed design solution with the users. Moreover, based on the increased understanding of the possible sources of the problems in interacting with the system, more concrete design recommendations may have been elicited even though that was out of the scope of the research work in the MMOtion project.

Table 5. Summary of research study in Paper 3

	Domain	**Methods**	**Participants**	**Year**
Research study	NPP process control	Document analysis, systems usability case, tools-in-use, simulator study, interviews, observation, questionnaires	Designer (1), operators: French (2), Finnish (2).	2010
Research question	Research question: How can participatory methods for expert-user reflection on work – including both exploring and evaluating individual task demands and future development prospects – be furthered to better integrate human and social considerations in safety-critical system design? Sub-question 2: Can functional modeling of work be used as a methodological means to facilitate expert-user reflection on work and as a presentation around which constructive discussion between the designers and users can take place early on in the design process?			
Paper	Paper 3: Koskinen, H. Book Chapter 4: Foreseeing: How to uncover the promise of solutions for future work. In Norros, L., Savioja, P., & Koskinen, H. (2015) Core-Task Design: A Practice-Theory Approach to Human Factors, Synthesis Lectures on Human-Centered Informatics, 8 (2), pp. 1-141.			

3.2.2 Developing tools for future smart farming

In a project called SmartAgriFood, a Future Internet (FI) supported smart farming system was developed (Table 6). The specific activity that the project focused on was pesticide spraying. The global food chain challenges – that is to say, food safety, environmental, ethical, and sociocultural issues – are all aspects that need to be carefully considered when developing future food chain activities (i.e., food production and consumption). For example, there are demands for more transparent food production due to consumers' increased interest in knowing the origin of the food products they purchase and consume daily. Furthermore, there has been a lot of discussion about how profits are divided within the food chain. It is expected that FI would enable new kinds of services and products that can be radically useful in addressing global food chain challenges and change ways of operation. Thus, in the project, the domain-specific requirements for FI and specific applications for smart farming were developed.

To appropriately elicit the requirements and develop meaningful applications, it is essential to understand the context and user needs. Consequently, systematic efforts were made in the project to better integrate human factors and participatory processes empowering the end users and other relevant stakeholder groups in design. Within the project, two types of user interventions were organized. Throughout the project, national discussion panels (four panels) were hosted in which different food chain actors could discuss and express their ideas and concerns about the functioning of the future food chain. Furthermore, interviews and smaller design workshops were organized with specific end-user groups such as spraying contractors and farmers. The functional modeling approach – that is, Tools-in-Use modeling – was systematically used in all interactions with the food chain actors. Through the models, the operational qualities of the emerging new system were jointly examined. The human factors experts working in the project together with the agricultural engineers developed the initial models. The models were then presented to and explored with the food chain actors in a series of panels and workshops organized within the project. After each user intervention, the models were revisited and developed further (altogether six different functional models were introduced in different phases of the development process). A total of 82 Finnish food chain actors were involved in the development of the smart farming system. Data collection was quite extensive. All the discussions within the national discussion panels and the design workshops were audio-recorded. In addition, field observations were conducted concerning the pesticide spraying. At the end of the project, a questionnaire study was organized to elicit subjective opinions and evaluations from all the participants individually.

In the SmartAgriFood project, there were two significant differences in the use of functional models in comparison to the MMOtion project: 1) In the SmartAgriFood project, the functional models were developed throughout the design process whereas in the MMOtion project, the models were developed afterwards based on the design documentation; 2) In the SmartAgriFood project, the models were directly exposed and made available to the users, whereas in the MMOtion project, the models were used more as planning material (e.g., in scenario

selection and structuring the questions) for the user evaluations. In both studies, we noticed that even though the focus was on user interaction, the designers could also reflect on the models and found them useful in their design work. In short, functional models clearly provided them with illustrative representations that helped the designers view the system from an operational perspective, thereby facilitating the discovery of information needs, demands and potential new solutions within a development context. The aforementioned was particularly the case in the SmartAgrifood project.

The results of the SmartAgriFood project and the use of functional TiU models as a descriptive tool for user involvement are reported in Paper 4 of this thesis.

Table 6. Summary of research study in Paper 4

	Domain	Methods	Participants	Year
Research study	Arable farming, pesticide spraying	Tools-in-use, interviews, observation, national panel discussions, design workshops, interface mock-ups, use case scenarios, questionnaire	National discussion panels: 1. (14, end users 8, IT experts 6); 2. (11, end users 10, IT expert 1); 3. (23, end users 18, IT experts 5); 4. (15, end users 10, IT experts 5). Design workshops: 1. farmers 2; 2. farmers 2; 3. 15 (farmers 8, retail 1, IT expert 1, researchers 3).	2011-2013
Research question	Research question: How can participatory methods for expert-user reflection on work – including both exploring and evaluating individual task demands and future development prospects – be furthered to better integrate human and social considerations in safety-critical system design? Sub-question 2: What kinds of functional models of work should be used as methodological means to facilitate expert-user reflection on work and as a presentation around which constructive discussion between the designers and users can take place early on in the design process?			
Paper	Paper 4: Koskinen, Hanna; Norros, Leena. (2018) The participatory design of tools: Foreseeing the potential of future internet enabled farming. Journal of Interaction Design and Architecture(s), 2018, (37), pp. 175-205.			

3.3 Analysis of user involvement in the design of operating panel interfaces

Wall and desk mounted analog operating panel interfaces have been central in NPP process control from the beginning of the nuclear era. For decades, these panels have been the main source of information for CR operators whose primary task is to monitor and control the nuclear process, recognize disturbances and abnormal events that may affect safety and maintain the plant within safety limits. It goes without saying that the panels represent the main means of interacting with the system and they are thus the central tool of the operators. For that reason, it was necessary to understand more deeply what qualities the operators value in the operating panel interface and how they use them in operating the NPP process. Moreover, panel interface modifications in connection with automation renewal at the Loviisa NPP provided a good opportunity to review and analyze how the operators could participate in designing their tools (Table 8).

In analyzing user involvement in the design of operating panels, we focused on three different phases of the operating panel system's lifecycle. The first point of analysis was the phase when the analog operating panels were implemented and taken into use. For this purpose, in-depth interviews were conducted with the HSI designers of Fortum Power and Heat Oy. These interviews were followed by a panel interface walkthrough exercise in the training simulator of Loviisa NPP in which the CR operators and the trainers explained the content and operation of the panel interface in detail. The second reported phase in the panel lifecycle is the shift from analog technology to digital alternatives (e.g., large screen and interactive displays). In this phase, the CRs were partly digitalized, and some alternatives were considered for the operating panels. A new digital operating panel interface was developed to be implemented and used in the Loviisa NPP's new training simulator. We had a possibility to follow this development work closely within the O'practise research project in the SAFIR research programme. We conducted interviews with the HSI designers and organized a user study in the Loviisa NPP training simulator in which four turbine side operators were involved in testing the new panel interface. The third reported phase concerns the developments that are currently taking place. Advanced new technologies such as virtual reality and augmented reality solutions may also benefit NPP operation. For example, it has been envisioned that a virtual reality-based CR could provide a new and more flexible training facility for operator training. Within this phase, we have conducted an evaluation of the virtual CR developed by Fortum Heat and Power Oy. Two full operating crews (i.e., two reactor operators, turbine operators and shift supervisors) were involved in the virtual CR testing. Data was collected by means of observation, interviews, and questionnaires. A summary of the different user studies conducted within the operating panel design research study – whose results are reported in Paper 5 – is presented in Table 7.

Table 7. Overview of the studies related to the operating panel design

Lifecycle phase	Data collection	Subjects	Date
1. Phase: Analog CR	Interviews about the operating panel HSI	In-house designers (2), operators (2)	2005
1. Phase: Analog CR	An operating panel HSI walk-through	SS, RO, TO operators (3), simulator instructors (2)	2008
2. Phase: Digital turning point	An interview about the virtual panel HSI	In-house designers (3)	2011
2. Phase: Digital turning point	Virtual panel HSI evaluation (observation, interviews, and questionnaires)	TO operators (4)	2012
3. Phase: Future operations	Virtual CR HSI evaluation (observation, interviews, and questionnaires)	SS, RO, TO operators (6)	2016

The user involvement in panel design and the different user tests reported in Paper VI were formative type since user feedback was actively pursued in order to improve the panel interface.

Table 8. Summary of research study in Paper 5

	Domain	Methods	Participants	Year
Research study	NPP, process control	Interviews, interface walk-through, simulator study, observation, questionnaire, video & audio recording	Designers (5), operators (15), simulator instructors (2)	2005-2016
Research question	Sub-question 1: What kinds of participatory practices are currently taking place in safety-critical human-system interaction design? Sub-question 3: What kinds of contributions can expert users deliver for safety-critical systems design in different phases of the product lifecycle?			
Paper	Paper 5: Koskinen, Hanna; Laarni, Jari; Bergroth, Joakim. (2022) User Involvement in Design of a Safety-Critical Operating Panel System. International Journal of Industrial Ergonomics			

3.4 Planning user interactions within the HFE program for an automatic tram

The transport system is currently undergoing fundamental changes due to the increasing use of automation. New automation solutions are being introduced in all sectors of transportation; for example, technology developers are envisioning automated cars, metros, and autonomous ships. There are many reasons for this ongoing trend of stepping up the use of automation, such as demands for sustainability, efficiency, and safety, to mention a few. Within one of VTT's own research initiatives (i.e., SmartTram project) and user study, the focus is on public transportation and developing automatic solutions for trams.

Developing a tailored human factors engineering (HFE) program creates a basis for appropriately acknowledging human and social aspects in the design of safety-critical systems. This study developed a SmartTram project-specific HFE program including an iterative evaluation framework. A particular emphasis was on the involvement of relevant user groups and laying out the verification and validation (V&V) plan and the related simulator and training facilities in the project. The results of this user study are reported in Paper 6 published in International Journal on Computer Science and Information Systems (Table 9).

Table 9. Summary of research study in Paper 6

	Domain	Methods	Participants	Year
Research study	Public transportation, vehicle automation	Interviews, literature review, simulator, interface mock-ups	Tram drivers (4) (simulator requirements), instructors (2) (simulator requirements)	2019-2021
Research question	Research question: How can participatory methods for expert-user reflection on work – including both exploring and evaluating individual task demands and future development prospects – be furthered to better integrate human and social considerations in safety-critical system design? Sub-question 1: What kinds of participatory practices are currently taking place in safety-critical human-system interaction design? Sub-question 3: What kinds of contributions can expert users deliver for safety-critical systems design in different phases of the product lifecycle?			
Paper	Paper 6: Koskinen, Hanna; Aromaa, Susanna; Goriachev Vladimir (2021) Human Factors Engineering Program Development and User Involvement in Design of Automatic Tram. In the IADIS International Journal on Computer Science and Information Systems.			

4. Results

In this chapter, an overview of the main results is presented. The detailed results are described in the papers attached at the end of this thesis.

4.1 Expert user view in safety-critical system design

Chapter 2 Related research pointed out that the expert users are ultimately the problem owners in the context of safety-critical system design. The expert users use their tools in managing and controlling the object of their activity (e.g., power production process). Over the years, expert users gain a lot of training and practical experience, and they may carry out many of their daily work activities and tasks subconsciously as automated operations, in a way that they might not find easy to verbalize or explain. Inspired by Vygotsky (Vygotsky, 1978), the functions that the tool may serve in an activity may be called tool functions. Accordingly, well-functioning tools may enable the expert users to comprehend the potential (i.e., psychological tool function) and effectively (i.e., instrumental tool function to produce the intended effect in the environment) act on the object of an activity as well as convey meanings (i.e., communicative tool functions) within the specific work community. As such, the tool functions provide one perspective on evaluating the appropriateness of a tool, that is, the systems usability (Savioja, 2014a).

The reviewed research (in Chapter 2) indicated that even if the expert users are not verbally able to separate these characterizations of tool or be conscious of them, these expert users are the ones that possess the most first-hand experience of their tools and how they function in different operational situations, which makes their opinions particularly valuable. Thus, the expert users' subjective experiences and professional knowledge on using the tools in their goal-oriented activity can be a valuable source of information for safety-critical system design as well. Based on their earlier experiences of using different tools in their work, the expert users may be in a special position to estimate the promise of a design solution (or even a design idea) and whether it has potential to develop a meaningful tool for their activity. For that reason, the expert users' experiences and knowledge should be collected, as they are important in the design of safety-critical systems.

4.1.1 Knowledge contribution and subjective experiences of expert users

The design of safety-critical systems (particularly design in the nuclear domain) often follows a conservative strategy and relies on dogmas and standardized solutions that have been found to work in the past. In the reviewed literature in Chapter 2, the value of expert users' operative knowledge and experiences of the design of new tools were emphasized. In addition, in the systems usability construct developed and applied in the VTT's human factors team's research work, user experience (UX) is valued as one indicator of system appropriateness. Within systems usability, the UXs of the users are utilized as anticipatory indicators of the effects that the new system/tool will have on usage activity. This general feeling of expert users should not be dismissed in the design of safety-critical systems. For example, when after testing the system, an experienced operator has concerns about the suitability of some aspect of the proposed design solution, the experience should be taken seriously, and the source of these hesitant feelings should be investigated. Are the identified issues such that they may hinder the development of the technology into a meaningful tool for the operating activity and, if so, what are the particular characteristics of the solution that should be further improved? According to the reviewed literature, the expert users' opinions were most often utilized in connection with usability evaluations. Moreover, the systems usability construct suggests that the UX would be especially valuable in evaluations during the early phase of the design, as the maturity of the design solution does not yet allow the meaningful use of other measurements such as performance metrics (e.g., execution times and errors). The expert users, however, possess operative knowledge that certainly goes beyond merely contributing to traditional user testing and evaluations. The expert users who operate the safety-critical system daily are the persons most qualified to provide input for the design even though their insights are often not articulated in the form of traditional design recommendations.

In the three phases of the operating panel interface design presented in Paper VI of this thesis, the motivation was to investigate how the expert users were involved in the design throughout the panel HSI lifecycle and what was the specific quality of the expertise that they contributed to the design. The operating panel interface is one of the central tools that the operators use for monitoring and controlling the NPP process. These panels with their blinking indicator lights may tell them in a fraction of a second if anything abnormal happens in the process. Moreover, the panels provide very tangible feedback from the control operations, unlike screen-based interfaces, as well as allow the use of several different operating strategies (e.g., operating many individual pumps simultaneously by pressing multiple control buttons at same time). It has also been suggested that panels support the shared awareness of the operating crew, as the location of the crewmembers can indicate what they are working on at a given time. Thus, over the years, the operating panel interface has become a meaningful tool for the operators, and many operations have become subconscious, as they can be executed efficiently without the need for conscious guidance or monitoring. Therefore, any efforts to develop and modify the panel interface should be sensitive to the feelings and opinions of the operators.

In the first phase, the operators contributed to the panel HSI in two ways. First, they actively helped reconstruct the operating panels after the vendor-installed panel setup was found to be confusing and inadequate for operating purposes. Thus, the operators were directly involved in the design of the new panel setup, and they could contribute by constructing a representation of the process that is a better fit with their mental models (see 4.3 in Figure 14). However, in this case, the user involvement was not planned beforehand, but was instead a reactive response to suddenly identified HF issues and unsatisfactory design outcomes from the operational point of view. The second contribution that the operators made in the first phase was their participation in the panel walkthrough exercise that was organized to understand more profoundly the use and meaning of the operating panels as a central tool of the NPP operators. This walkthrough exercise was not directly related to any specific design project; it was known that in a couple of years it would be timely to modernize aspects of the CR and HSI systems. The user contributions were clearly associated with explaining the tasks and requirements of performing panel operations and these could serve as future design inputs (i.e., capturing operator needs and expectations concerning the operating panels).

In the last phase, a virtual reality-based CR was developed. The virtual panels were implemented in this virtual control room environment as well, and the operators were brought in to experience how it would be to operate the process in a virtual environment (see 4.2 in Figure 14). Many potential applications and functions for the virtual control room were envisioned by its developers, including design and development of HSI, testing and evaluation activities as well as operator training. After getting some hands-on experience of the operation of the virtual control room, the operators could critically reflect on the fulfillment of the user requirements and generally give feedback on how realistic the virtual control room is as an operating platform (see 4.3 in Figure 14). This enabled them to make a valuable contribution to refining and shaping the different characteristics of the virtual control room.

4.1 Set requirements through contextual knowledge	**4.2** Envision future possibilities grounded on past experiences	**4.3** Critical reflection on fulfillment of requirements

Figure 14. Knowledge creation framework in participatory simulation by Andersen and Broberg (Andersen & Broberg, 2015)

As a conclusion, within the operating panel interface study presented in Paper 5, the operators were involved in the design in different phases of the panel HSI lifecycle. The experiences of the operators of the panel HSI provided rich contributions to the design that went beyond the customary type of user feedback reached in usability testing and validations. The valuable contributions of the operators also motivated the designers to involve users in a more active and permanent manner. However, the participatory processes and user involvement as such were still not managed systematically or supported methodically, and a lot depended on the interest of the individual designers working in the organization to actively seek the users' feedback.

4.1.2 Contextual demands of work

To successfully take care of safety-critical work tasks (i.e., fulfilling the objectives of the activity) the actor (i.e., expert user) needs to take into account the possibilities and constraints of that specific work environment. Similarly, in designing tools for safety-critical work, it is essential to carefully analyze the contextual demands of the particular object of work activity for which the tools are intended to be used. This contextual understanding of the demands of the work activity can be further used, for example, in eliciting design requirements for HSIs or designing procedures. Norros (Norros, 2004) has introduced a method called core-task analysis that is actively used by VTT's human factors team – this method makes it possible to model the human role and work demands in a more elaborated manner by specifying the actual possibilities and constraints of an activity. The notion of core task is used to functionally describe the main content of the work. First, the dynamicity, complexity and uncertainty features of a specific work environment are elicited. Then the activity is viewed from the perspective of the human resources, that is, from the perspective of the actor's skills, knowledge and collaboration and reflection resources. Finally, when the use of human resources related to managing/coping with the features of the environment in achieving the objectives of the activity is analyzed, the core tasks of the specific work activity can be deduced. The contextually defined core-task functions provide knowledge about what features of the specific environment should be mediated and supported by the tools so that the goals of the activity can be successfully achieved. Analyzing the core-task functions requires empirical data sourced through user interviews and observations of work activity, for example.

Acquiring the contextual understanding is often done through a specific core-task interview procedure. For example, in the context of smart farming discussed in Paper 4, the core-task demands for farming activity were modeled based on interviews with the farmers and the spraying contractors. However, other sources of information exist as well. For example, in the MMOtion project in the process control context described in Paper 3, the already existing and available design documentation, especially the section stating the requirements of operator work, was used as a basis for modeling the core task demands of the work of the turbine side operator.

4.2 Design process of safety-critical systems

Safety-critical systems may set special challenges for engineering and the design process. Safety-critical system design is often strictly regulated, and several standards and restrictions are introduced concerning both the design process and the end product (i.e., the design solution). For example, in the design of new CR and HSI systems for NPPs, a conservative design strategy is followed. The conservative design strategy entails the idea that design solutions that have been found to work well should not be interfered with lightly without rigorous analysis and justification. From the human factors and HSI design point of view, following the conservative design strategy means that the conventional design

principles also dominate in the development of the new solutions and, for example, introducing advanced technologies and contemporary ideas and understanding about the human-system interaction paradigm and human cognition is a time-consuming and sometimes even a troublesome process. Of course, improvements to HSI design are also conducted in the nuclear field when, for example, some elements of the HSI become obsolete, but these changes are often incremental and almost never as radical as, for example, the FITNESS HSI design concept that was evaluated and discussed in Paper 3.

4.2.1 HFE program and integration of HFE in design

In addition to the conservative design approach and strict regulatory demands concerning the development of new solutions, based on the reviewed literature (in Chapter 2), many other issues pose challenges to safety-critical system design as well. For example, if the operative lifecycle of a NPP is long, so too is also the design process whenever any development or modernization projects are initiated. An extensive automation modernization project may take several years to carry out from the drawing board all the way to the implementation and commissioning of the new system. The lengthy design process and the present-day desire to incorporate other lifecycle considerations also call for better integration of diverse engineering knowledge and improved knowledge management practices. In Paper 6, it was stated that the human factors engineering activities should be planned as an integral part of the lifecycle activities of the safety-critical system and should be considered at all levels of engineering design (aspects also discussed in documents such as IEEE 1023-2004 and IAEA NP-T-3.10). As a cure to this engineering management issue, drafting a systematic and integrated HFE program for each individual development project was proposed in Paper 6. Within the HFE program, the needed HF activities, their scope, extent as well as schedule and the needed resources are planned and specified in detail. Table 10 outlines the basic structure of the HFE program regarding the Smart Tram project. However, because the projects are initiated from different kinds of starting points and realized in a variety of organizational contexts, it is likely that the HFE programs always need to be individually tailored to best fit each specific situation and the needs of the project.

Table 10. The general outline of the HFE program for the Smart Tram project. Abbreviation: PoUI = Points of User Interaction.(Koskinen, Aromaa, et al., 2021)

Input	Design process	Output
• Need for change (e.g., growing number of passengers, sustainable and environmentally friendly public transport solutions) • Existing concepts (e.g., proofs of concept, level of automation) • Operational experience (other automated traffic solutions, e.g., metro)	**Initial clarification and analysis** (impact, needs and constraints, HFE goals) PoUI **Operation:** Tram driver & traffic control center personnel (interviews) **Service:** passenger & road users (surveys, interviews)	• HF input to project plan (identification of relevant user groups) • HFE program/ activities (i.e., tasks, schedule and resources) • Preliminary evaluation schema (i.e., SUC, subsystems and integrated system validation)

Input	Design process	Output
• Operating environment description • User and safety requirements • Standards	**Requirements and concept design** (ConOps, task analysis, user requirements) PoUI **Operation:** Field observation. Explorative prototyping and testing with tram drivers (field, simulator) **Service:** Passenger & road users (e.g., focus groups)	• SmartTram concept (level of automation, documentation of ConOps, user interaction) • Project requirements set • HSI style guide (e.g. main design principles, HSI guidance on layout, alarms, navigation, color coding etc.)
• I&C architectures • Standards	**Detail/integrated design** (user interface, training design) PoUI **Operation:** Iterative development of solutions with tram drivers (simulator, workshops) **Service:** User testing with passenger & road users (simulator, workshops)	• Tram user interface and interior solution
• V&V plan (e.g., user groups, scenarios, acceptance criteria) • Standards	**Verification & validation** (simulations, validation tests) PoUI **Operation:** SSV and ISV tram drivers (simulator) **Service:** ISV passenger & road users (simulator)	• V&V record (identified human engineering discrepancies, design feedback, decisions on further design iterations)
• Training curriculum	**Implementation, commissioning** PoUI **Operation:** Operating experience of tram drivers (field) **Service:** Customer experience of passenger & road users (field)	• Accumulated evaluation record (document early operating experiences)

The tailoring of the HFE program is necessary, as it may be, for example, that many relevant but substantially different user groups are identified that require different kinds of HF attention and in different phases of the design process. One example is the SmartTram project discussed in Paper V, in which one important group of users comprised the tram drivers whose work tasks were about to radically change from operative driving tasks to the monitoring of the automatic driving systems. The future passengers of the automatic tram with their specific preferences and expectations represented the other essential user group to be involved in the development of the new automatic transportation solutions. The type of contribution and user knowledge, however, that these two user groups (i.e., tram drivers and passengers) could provide to automatic tram development were completely distinct from each other. Consequently, it is argued that in safety-critical system design, a tailored HFE program is needed to systematically and appropriately address all the activities and user groups that require HF attention. In Table 10, the points of user interaction with the relevant user groups are defined. Drafting a HFE program may also support collaboration with the other engineering disciplines working in the project as the inputs and outputs (e.g., documents) of different development phases are clearly stated. Moreover, it can be easily seen what kinds of investigations and understanding the design solution are based on, thus supporting the general requirement to carefully document both the process and the details of the final design

solution that is expected in the context of safety-critical system design. Planning and clearly stating the points and types of user interactions within the HFE program may help in coordinating and optimizing the HF efforts more efficiently but also immediately reveal if the user view is not appropriately addressed in some stage of the design process.

4.2.2 Maturation of the design solution

Regarding the issue of involving the expert users in the early phases of the design process requires considering the maturity and form that the design solution has in different phases of its development. The expert users' contribution and involvement in the different phases of the design process was discussed in more detail in Paper 5 and illustrated in Figure 15. The design process often begins from an idea or a recognized need for a change (see Figure 15, row 3, cell 3.1). In this early phase, there are still several directions and material forms that the design can later take. Then, when the design proceeds through iterative design-evaluation cycles, the design solution assumes a more matured and defined form, and simultaneously the latitude for changes and design alterations becomes narrower. In other words, at the early phases of the design process there is the most potential for effective design decision-making and developing the design. The same issue is exemplified with the often-discussed design-to-cost cycle, which is illustrated with two crossing curves within the axis of effort/impact and time – when the design process is further along, the ability to impact cost and the functional capabilities of the design solution decreases whereas the cost of making changes increases. Thus, reaching a proper socio-technical understanding of the problem space and the design task at the beginning of the development process would be most beneficial (both economically and functionally) in achieving a successful design outcome (i.e., useful product/a meaningful tool). However, when the design solution has not as yet reached a very mature form, it may be more difficult to address and discuss the different characteristics of the solution; yet early evaluations and user feedback through testing and explorations would be essential. In the concept design phase, when the design solution can be addressed in a more mature form with a drawing or mock-up of some sort, the discussion between designers and expert users may already be easier (even though, according to the reviewed literature in Chapter 2, in the concept design phase the difficulty of providing tangible demonstrations is still often recognized). When the expert users can experience and test the new solution hands-on in the form of a functional prototype or a product, that is, when the design process has proceeded to the detail and integrated design phases, contributions from the user evaluations are most concrete and easy to obtain. However, in these late phases, there are only remote possibilities to do any substantial changes to the design without incurring high costs, even if the user studies would indicate the need for such changes.

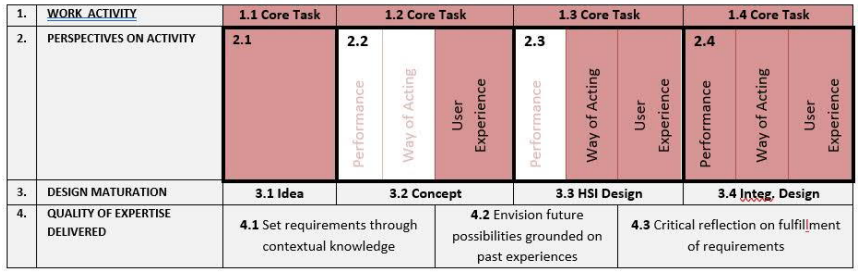

Figure 15. A summary of the qualities of expertise delivered in the design by the expert users in different phases of the design process.

Example 1: Exploring multitouch-based interaction in the context of process control

The explorative user study presented in Paper I assessed whether multitouch-based interaction would benefit the process control activity and be more intuitive and direct than the predominantly used mouse-based interaction. The test setup for investigating the idea of multitouch-based interaction in process control was realized without any graphical illustrations or HSI mock-ups by simply using a Plexiglas board (size of 97 cm x 58) to imitate the surface of a multitouch screen and a carefully drafted test manuscript.

Much was left to the imagination of the test persons interacting with the Plexiglas according to the given instructions. The results showed that users preferred interaction with the display screen in which the used touches were short in duration and light in terms of the amount of force used in pressing. Moreover, the users associated specific types of hand gestures with specific operations such as zooming in or out or activating some particular command. Based on this explorative study investigating touch-screen interaction in process control, I conclude that users' knowledge and experiences are significant in informing the design of a new tool and it is possible early on to gain insights into the potential of the new design idea to develop a seriously taken tool in work. Furthermore, implementing explorative studies with expert users in early phases of the design process does not always need to be a laborious and costly effort (e.g., a demanding simulator of some sort) and can still produce meaningful design feedback that can direct the further development of the design solution.

Example 2: Interactive large-screen displays in an outage control center

Paper 2, included in this thesis, presents the results of a research study that was realized collaboratively by two international research organizations, OECD Halden Reactor Project and VTT Technical Research Centre of Finland. The research study was future-oriented, aiming at exploring novel human-system interaction concepts for future NPPs. The particular topic of the study was outage operation and how interactive surfaces could be used to benefit collaborative activity in Outage Control Centers (OCCs), from which outages are managed. An outage is an activity in an industrial plant that takes place at regular intervals (usually annually) and during which a variety of maintenance and repair works (i.e., an average of 12,000 activities and work items) as well as refueling are ex-

ecuted. The main objective of the outage operation is to carry out all these activities in a safe and efficient manner. In the first phase of the project, experienced outage personnel were involved in setting the requirements for the new display concept. A series of interviews were carried out at the South Texas Plant in the U.S. and a design workshop with one experienced outage shift supervisor from U.S. PWR was held at Halden Norway. The interviews were facilitated with different outage materials such as outage schedules printed on paper canvases. Based on these user interactions, concept level requirements for the interactive tabletop system in OCC were elicited (see Figure 16). The detailed description of the results of the contextual inquiry is presented in Paper 2, included in this thesis.

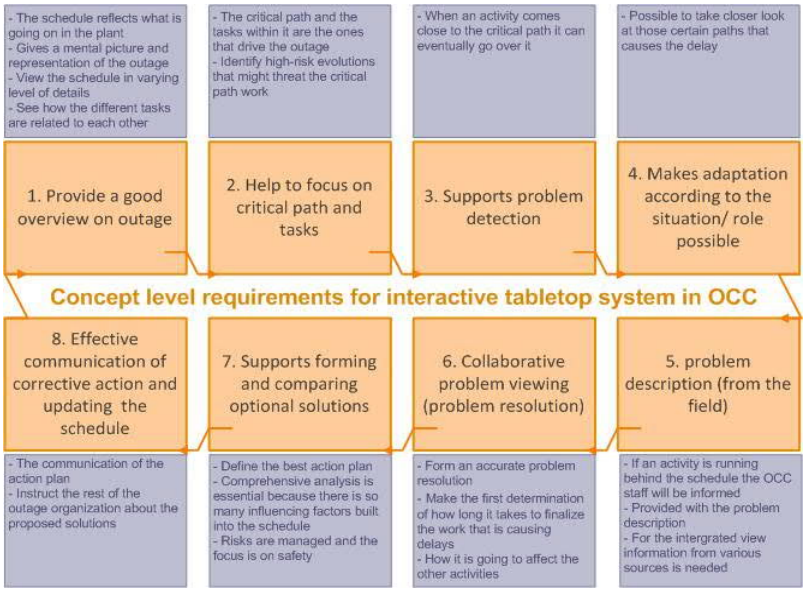

Figure 16. User requirements for the interactive tabletop in OCC (Koskinen & Hurlen, 2011)

Following the contextual inquiry, initial design ideas were explored through prototyping activity in design workshops. The used prototypes were mostly low fidelity paper mock-ups and sketches that were explored together with expert users and designers. In the last phase of the project, a video prototype was produced from the ideas that were experienced as being most promising. The video prototype was then used for obtaining feedback about the tabletop concept from a larger audience. Overall, the study demonstrated how important it is to create a good contextual understanding of the activity based on the initial design ideas that can be developed further. Even with low fidelity paper prototypes and verbal characterizations of the possible design solutions, valuable user feedback was obtained, contributing to the further detailing of specific interface features (e.g., outage schedule manipulation). With the video prototype, it was possible to demonstrate the functioning of the main concept solutions of the tabletop design.

4.2.3 Human factors evaluation of the design solution

Iterative evaluation of the design solution is an integral part of the HFE program and required in the context of safety-critical system design. Indeed, this is the case when, for example, the formal evaluation of a new design solution has to be undertaken in a large-scale modernization project or an upgrade/modification of old systems. In safety-critical system design, evaluation may be an especially demanding, lengthy and regulated process. For example, NUREG provides guidance on carrying out the evaluation activities within NPP modernization and upgrade projects; however, these documents have a strong emphasis on the late-stage final evaluation that should be conducted with the finalized design solution, that is, on integrated system validation (ISV). Consequently, as many of the authors of the reviewed literature have also pointed out (in Chapter 2), the other types of evaluations (those that are more formative by their nature and executed at an early stage of the design) are not so thoroughly addressed – for instance, in Figure 17, the ISV is just one point of the system lifecycle in which HF evaluation should take place.

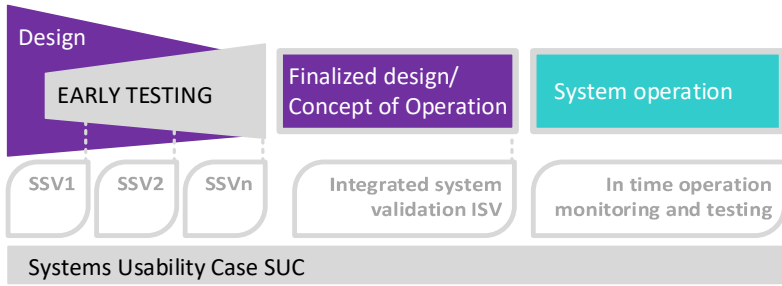

Figure 17. A lifecycle view of safety-critical system V&V process

HF evaluations should be iteratively implemented from the beginning and during the design process to ensure success when the design reaches the ISV stage. For example, in a design stage when some of the subsystems have been completed, a subsystem validation (SSV) procedure could be followed. However, even more early-stage formative evaluations and testing of the system should be pursued in safety-critical system design so that a proper human factors view can be implemented. For HF evaluations and analysis that may take place before the actual design project, the term post-formative evaluations have also been used (see Chapter 2.4.2). One example of such post-formative evaluations is an expert review prior to the design phase, which provides expert input for the planning and analysis of the design; another example is baseline evaluations that aim at creating a picture of the state of current operator or system performance. Paper 5, included in this thesis, reports on a panel walkthrough exercise with the NPP operators that provides a good example of the kind of post-formative HF evaluation that yields useful design insights from expert users. In a similar vein, when the system has been completed and deployed, HF evaluation activities that aim at longitudinal performance monitoring should be

considered. For these types of evaluations, the term post-summative evaluations have also been used (see Chapter 2.4.2); such evaluations could be done, for example, in connection with operator training by carefully following the operators' interaction with the system and collecting feedback. Thus, the ISV should not be considered as an end, but rather as a starting point from which the newly introduced design solution can start developing into a meaningful tool. This idea was also referred to by one experienced HSI designer whose interview is reported in Paper 5, which described the NPP CR as evolutionary design, that is, the CR should be seen as a continuously developing entity that can never reach a fully completed stage. Thus, the tool develops all the time, and the expert users may even do their own small modifications and improvements to it over time.

Sub-question 2 concerning the development of methodological means to facilitate expert-user reflection on work and inclusion of expert users' contribution at the early stage of the design process originated from the need to better support formative evaluation (i.e., evaluation that is done during the design to improve the design solution as it evolves) or the HF analyses that are done prior to the actual design. VTT's human factors team has developed a human factors evaluation approach called Systems Usability Case (SUC) (see lowest bar in Figure 16). SUC is based on safety case thinking and the notion of systems usability, but also borrows ideas from other fields of engineering such as continuous engineering and multi-stage validation. SUC is defined as aiming at "creating an accumulated documented body of evidence throughout the design that provides a convincing and valid argument of the degree of usability of a system for a given application in a given environment" (Koskinen, Laarni, et al., 2021; Liinasuo & Norros, 2007). Thus, the evaluation approach is meant to be used in a longitudinal manner throughout the design process and provides a documentation of the human factors data concerning the design solution. SUC has been employed successfully in subsystem and integrated system validations, which are also depicted in Figure 17. In both types of evaluations (i.e., SSV and ISV), the testing activities have been carried out in advanced simulator environments (e.g., full-scope NPP training simulator). Even though SSV by its nature is more formative and the idea is to gain design feedback to inform the further refinement of the design solution, it may still not be considered to represent very early-stage evaluation. Expert users could potentially contribute much more extensively at the early phase of the design process, such as by taking a stance on the design rationale (e.g., descriptions of operating environment and user requirements) and participating in defining the different characteristics of the design solution both at the conceptual and interface/HSI level. In Paper 3, included in this thesis, the SUC approach was exploited in the evaluation of an innovative HSI concept. Whereas in Paper 6, a V&V process was developed for the SmartTram project in which iterative evaluation would be carried out from the beginning of the development process and the systems usability case approach would be used as an evaluation framework and for documentation of the results of the evaluations (Figure 17). This would be the first time when the SUC evaluation approach would be used systematically from the very beginning of the design process. It

is expected that new insights about the type and form of user contributions at early-stage design can be gained as well as how the evaluation documentation starts to accumulate evidence in favor of or against the promise of the design solution.

4.3 Participatory method for expert user involvement – functional approach

This subsection presents the results concerning the methodical research questions related to practical ways of facilitating participatory processes and especially the involvement of expert users in the design of safety-critical systems. In the review of related literature (Chapter 2), the following development needs were identified: 1) there should be more emphasis on gaining formative design feedback early on, 2) which would be contextual and enable more thorough analysis of the work activity, and 3) aid in discussing the new design solutions at different levels of abstraction (i.e., address the complexities and help seeing the causal relations).

4.3.1 Functional modeling in design

It has been made an inquiry into the use of functional modeling of work as a methodological means to facilitate expert-user reflection on work and as a presentation around which constructive discussion between the designers and the users can take place. The central interest was in the expert user involvement in the early stages of the design process of safety-critical system design.

With the aim of developing methodical means and broadening the repertoire of participatory design tools (from the predominant use of different prototyping techniques identified in the review of relevant research) the feasibility of functional models was investigated. Functional models seem to have potential, as they are structured representations of functions (i.e., purposes, activities, actions, processes, and operations) within the modeled system or subject area. The aim of functional modeling is to produce a behavioral model of the system under construction. Thus, a structured description of how the different system functionalities must cooperate in achieving the operational purpose/goal of the system may be created. Consequently, the functional models may help comprehending the means-ends hierarchy of the system, that is, to connect the upper-level goals and system functions to lower-level physical means. In doing so, the functional modeling may result in a tangible and illustrative representation of the modeled entity and help to view the system from different levels of abstraction. The analysis of core-task demands referred to in subsection 4.1.2 can be seen as one type of functional description of the work activity. The benefit of functional modeling is that it may offer the possibility to comprehend the work system in more generic and conceptual terms (i.e., focusing on the functionalities), without necessarily anchoring the structural means required for achieving the intended functions. Thus, the functional models seem especially promising in dealing with the design ideas in the early conceptual phases of the design process, yet provide a natural way to start discussing the physical means that

become topical in the later stages of design, that is, the detail and integrated system design phases.

4.3.2 Tools-in-Use modeling

To build a foundation for a constructive discussion between the designers and the users about the promise of design solutions, a functional modeling approach called Tools-in-Use (TiU) has been developed. As the name of this modeling approach suggests, it aims to depict the emerging new design solution (i.e., tool) in a contextualized way alongside the work activity that it aims to serve. This specific aspect of the TiU models, that is, presenting the tool together with the task demands, invites the different design parties (i.e., designers and users) to gather around a presentation that both sides may find somewhat familiar. This supports constructive discussion, as the model provides a basis that all the participants can relate to one way or another. In the context of participatory design research, Muller and Druin (Muller & Druin, 2012) have discussed "the third space of participatory design," by which they refer to the design parties moving out from their accustomed "territories" to neutral ground not owned by anyone in particular, which allows them to together develop the new rules and prospects to be commonly shared. Similar to this idea, the TiU model creates a kind of third space that includes characteristics from both design parties' worlds. That is to say, the core-task demands represent the contextually meaningful content of the work activity (i.e., the expert user's world) and the analysis and description of the problem-solution space something typical for designers in their everyday design world. Thus, the TiU model provides an arena in which the collaborative construction and discovery of the new design solution can start to emerge through negotiation, with the potential to develop a meaningful tool.

One principal idea in user-centered design is to base the design on an appropriate understanding and analysis of user needs and preferences. The TiU model aims to make the work activity explicit so that informed design decisions can be made. The core-task analysis produces a generalization of the present work activity in the form of stated core-task demands and therefore creates a contextually grounded basis for analyzing the future value of the new design solutions and for projecting potential concepts of new work. To emphasize the mediating role of tools in work, the technical enablers and the main innovative functionalities of the proposed new design solution are analyzed and made explicit on a detailed level in the TiU model.

4.3.3 Procedure for constructing the Tools-in-Use model

In developing TiU models, first, the work activity and the technological enablers are analyzed together with the end users, which then enables the values of the future system, its major innovative functionalities and the operation of the system in practice to be portrayed and comprehended. The resulting TiU model presents the higher-level functional goals (e.g., the functional task of human actors) in connection with the lower-level physical means (e.g., individual interface elements and design solutions).

Three distinctive levels aim to capture the particular properties of the functionalities of the joint human-technology system and form the basic structure of the TiU model (see Table 11). The "value level" is the uppermost level described in the TiU model and the level from which constructing the TiU model is started. The value level, as its name indicates, aims at describing the use values that are connected to the functioning of the system. Within the value level, at least the core-task demands as a functional description of the main content of that specific work are analyzed according to a core-task analysis procedure. That is, the core-task functions are analyzed and comprehended based on enquiry (e.g., by means of interviews and observation of work) of the generic features (i.e., dynamism, complicity, and uncertainty) of the work domain and the type of human resources (i.e., skill, knowledge, and collaboration and reflection) applied in the work. While obviously the description of the core-task functions comprises the central content of the value level, the value-critical user experiences (e.g., in the form of UX goals (Kaasinen et al., 2015; Koskinen et al., 2013a)) and business "value" propositions affecting the operation of the system may also be stated and under discussion in this level. Following the value level, a description of the main functional content of the work (i.e., core tasks) in the second intermediate level – the HSI concept level – of the proposed technology concept is outlined. The HSI concept level is described from two distinct vantage points: the first is the functional requirement point of view and the second the concept solution view. The importance of domain-specific expertise is often highlighted in constructing the HSI concept level, even though eliciting the functional requirements and forming the concept solution is meant to be a dialogic thinking process and iterative design activity between all the design parties. In the description of the requirements and the solution, the HSI concept level's connection to the value level is elaborated from the perspective of the potential support of the concept to the defined core tasks. At this phase of the modeling, similar content and questions are worked on as when, for example, drafting concept of operation documentation. The last and most concrete level of the TiU modeling is the user interface level. At this level, the requirements and content of the user interface are explicated and stated from the usage point of view. Consequently, a picture and an understanding of how the functionalities of the system become affordable and realized should start to assume a very tangible form. It is often easiest for both designers and users to deal with the user interface level of the TiU model as it is the most concrete level and, furthermore, the proposed new tool may already be experienced in the form of a functioning prototype of some sort. However, the TiU modeling approach allows easily drafting and exploring alternative ways to realize the support for the core tasks, as the user interface solution is described in written form. In the modeling, it is not beneficial to become fixated on some specific user interface solution too early on in the design process because it is likely that there are many possible material means to fulfill the core-task functions.

Table 11. The generic structure of the TiU model

Level	Content	Description
Value	The core task	The generalized control demands of a particular work, as mastered by means of a human actor's skill, knowledge, and collaborative resources
	Business propositions	A value proposition is a promise of value to be delivered
	User experience	Value-critical user experiences
Con-cept	Concept requirements	The concept level functional requirements indicate what kind of qualities the future system should provide for the users
	Concept solution	The concept solutions indicate the main ideas/construction of the elements that contribute to the delivery of the required functions
User inter-face	UI requirements	The UI requirements indicate how the elements of the interface should be organized for the interface to be, e.g., usable, effective, and aesthetically appealing
	UI solutions	The UI solutions indicate the main ideas/construction of the elements that realize the user interface as it would be implemented into use

Ideally, the work modeling and handling of the TiU model would be initiated at the beginning of the design process. The functional view would allow a better focus on the critical functionalities that are needed in achieving and appropriately addressing the object of the activity instead of introducing products, for example, through a technology push or on the basis of another distorted view. The TiU modeling, however, can attend to any phase of the design, yet it directs to revise the value base, that is, the functional design rationale and the user point of view at the value level.

4.3.4 Example 1: Foreseeing the potential of Future Internet-enhanced smart farming

In the SmartAgriFood project reported in Paper V, the TiU modeling approach was used as a basis for interacting with food chain actors in the development process of Future Internet-enhanced smart farming. The specific application area within the smart farming work package was pesticide spraying activity. The following is an explanation of the TiU models (one of which can be seen in Figure 18) that were developed and utilized within the SmartAgriFood project.

In the project, the smart farming system was described at different levels of abstraction through TiU modeling. Within the value level, the farming work and its core-task functions were analyzed and made explicit. In analyzing the core-task functions, interviews with farmers and the earlier research work on farming activity were utilized as a foundation for contextual understanding. The initial TiU models in the project were developed in close collaboration with the agricultural engineers working in the project. The work analysis at the value level was followed by progressing through the concept level ideas to drafting a particular design solution at the user interface level of TiU modeling and a discussion about the support that it may provide for the core task. The TiU model was handled together with the food chain actors in two different types of user interventions, that is, in national discussion panels and design workshops. After each interaction with the users, the researchers revised the TiU model according to the discussions and user feedback. Hence, the TiU models were further elaborated and refined based on the food chain actors' insights. The TiU models could also be readily edited during the user interventions as necessary. In later stages

of the design process, the developed TiU models were enriched with usage scenario descriptions and illustrative user interface mock-ups. While the scenario descriptions and interface mock-ups attempted to make the specifics of the developed smart farming system explicit, the functional TiU models were needed to highlight and interconnect these singular operational situations and solutions within the wider context of farming activity and the food chain. The operational scenario descriptions and interface mock-ups directly drew their content from the TiU models and therefore enabled users to easily make references to the higher abstraction levels of the TiU models (i.e., the value and concept levels) while exploring the individual user interface solutions through scenarios and mock-ups.

Altogether four individual TiU models (Table 12) were developed and explored together with the food chain actors during the project. The content of the models was closely related to each other, and the models were introduced in successive order in the user interventions, that is, in a series of national discussion panels and design workshops. It may also be claimed that the initial model became more precise and was further developed in the collaborative design process when the results of the joint exploration of the models were documented.

Table 12. The TiU models introduced in the user interventions of the SmartAgriFood project

User interventions	Name of the TiU model
Phase I: Shared construction of future smart farming	FI-supported smart farming model
Phase II: Collective discovery of smart spraying concept	Smart spraying concept
Phase III: Service framework as model-initiated innovation	Smart farming service framework
Phase IV: Shared agreement of the FI Promise for future smart farming	An integrated model of the smart farming concept

In the following, the content of the first two functional TiU models (Phase I & Phase II) are described with the idea of providing a tangible example of how TiU modeling can be used for involving users in the design process. The detailed level results are, however, presented in Paper 4 of this thesis.

In the first phase, there were two central objectives that covered 1) how the aims of the farming activity were seen in relation to the global food chain challenges (i.e., food safety, environment, sociocultural and ethical issues) and 2) what innovations FI was foreseen to provide for arable farming. A particular challenge from the participatory design point of view in this first phase was how to initiate a shared construction of smart farming and enable the creative agency of the food chain actors involved in the project. In Figure 18, the initial TiU model for FI-supported smart farming is presented. The model was prepared in close collaboration with the agricultural engineers working in the project. While the human factors specialist was responsible for modeling the core tasks of pesticide spraying and providing the general TiU modeling frame, the engineers led the drafting of the description of the technical characteristics of the spraying system. A TiU-specific tree-level structure was utilized (see the upper part of the Smart Farming box in Figure 18). However, in this early phase, the model did not as yet include the most concrete level of description, that is, the user interface level. In addition to the introduction of the smart spraying concept, in this specific model the concept's relation to the overall farming work process and the

three particular use cases selected to be in focus in the project (i.e., bad weather, work setup and machine breakdown) were depicted. The main aim was to provide a comprehensive illustration of the problem space for the forthcoming design work, that is, the statement of the core tasks, the overall work process and the specific situational demands, and thus facilitate further definition of the qualities of the smart spraying system. The model was walked through with the food chain actors; for example, it was highlighted how the specific functionalities of the future system would be exploited in different operational situations and the farmers could then respond by expressing if they had any additional task demands or knowledge requirements to carry out those spraying tasks appropriately. Through this kind of dialogic contemplation of the different aspects of the TiU model, a shared understanding of the context was created, which also enabled the further enhancement of the smart spraying concept.

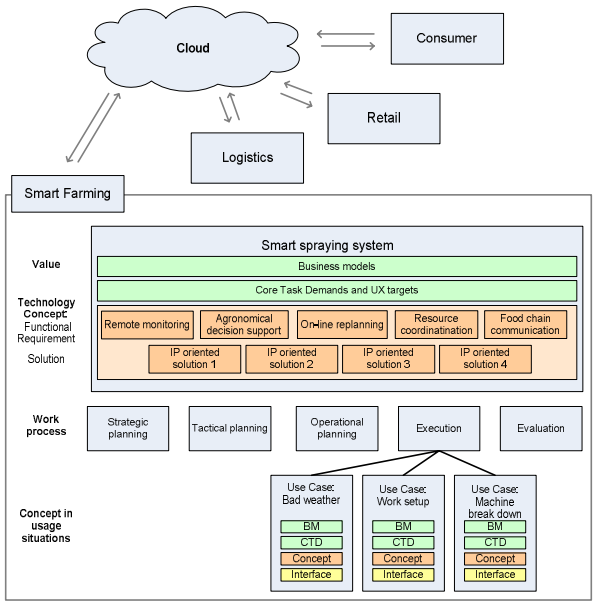

Figure 18. FI-supported smart farming model (Koskinen & Norros, 2018)

In the second phase, the main aim of the user interactions was to obtain more detailed user feedback on the benefits and value of the smart spraying concept. A new more specified and revised TiU model according to the results of Phase I – called the smart spraying concept – was introduced for this purpose (Figure 19). At the uppermost value level, the initial set of user experience goals and core-task functions were depicted. Nine specific user experience goals (*i.e., information security, trust within the community of network actors, quality of information and services within the FI smart farming system, cloud awareness: understanding the structure of FI, experience of continuity of service, timely responses, ease of use of harmonized solutions, joy of professional development, positive expectations of developing farming culture*) were elicited based on the user interventions in Phase I. In addition, the six core-task functions regarding the spraying activity were further elaborated (see the Core-Task

Functions line in Figure 19) and the Technology Concept concretized by stating the six functional requirements and the five concept solutions.

In Phase II, in the national discussion panel, the model was discussed at a more general level because not that many of the participants had firsthand experience of spraying tasks. However, the model was collectively explored, and several notes were made, especially regarding the user experience goals at the value level. For example, the panelists unanimously expressed that the metaphor of a cloud is too vague and does not provide a sufficient basis for judging the features of the concept. In addition, information security was seen as one central concern that may affect the acceptance and more extensive use of FI-based systems in agricultural production. However, the panelists thought that the aim of improving food awareness and a direct link to the consumers could be a major improvement that FI-enhanced smart farming could provide.

In the design workshops with expert users (i.e., farmers and spraying contractors), a more detailed discussion could be held about the proposed future functionalities of the smart spraying system. The TiU model was explored beginning from its value level and a discussion about the six generic core-task functions (i.e., *readiness to act, flexibility of acting and reorienting, interpretativeness of acting, conceptual mastery of the process, creating shared awareness* and *optimal sharing of efforts*). When exposing the expert users to the initial core-task definitions, they were asked if they could relate both themselves and the demands of the spraying task to the generalized description of the work activity. Furthermore, the expert users were encouraged to project the core-task definitions onto the proposed concept solutions (i.e., *tailoring services by combining internal and external data; aggregated recommendations for online decision-making; the task-aware and timely presentation of information; the context-aware reporting of decisions and tasks*; and *networked communication*). In exploring each concept solution individually, it was discussed what kind of support they may embody regarding the different core-task functions. The engineers explained the design rationale and how they thought that the specific solution contributed to the problem, and the expert users reflected on the solution from the perspective of how well it fit their everyday work practices. For example, concerning the concept solution for food chain communication, the expert users had high expectations, as they felt that there is no genuine two-way communication in the food chain, and they had difficulties with maintaining awareness of the market demand for their products. Enhanced food chain communication would allow them to provide more detailed and meaningful information about their products to the consumers (e.g., production history) but also a possibility to adjust their own production processes in line with the consumer preferences and market demand (e.g., organic production).

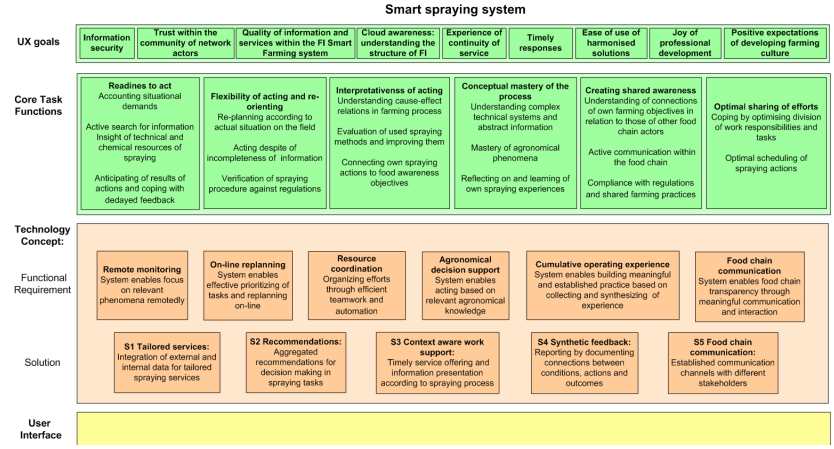

Figure 19. Smart spraying concept (Koskinen & Norros, 2018)

The discussions in both the national discussion panel and the design workshops provided confirmation about the potential benefits and value of the new innovative features of the smart spraying system. The perspectives of the different participants also enabled the informed further development of the specific characteristics of the smart spraying concept.

Two TiU models were then introduced in the project. They followed the same three-level TiU model structure. Between Phase II and Phase III, a TiU model-initiated innovative leap was taken (see Figure 19). In exploring and refining the smart spraying concept model and the concept promise that it contained, the agricultural engineers recognized a gap. Even though the concept was generally considered promising, the expert users lacked a channel that would allow them to employ the smart spraying concept effectively in their everyday farming work. It seemed again to be a standalone system that might cause just more management and interoperability issues. This observation initiated the idea of a farming service framework that exploits the FI to achieve seamless integration of all kinds of farming system, equipment, and information services (for more information about the technical construction of the smart service framework, see (Pesonen et al., 2014)). The framework following from this specific expert users' concern was designed to enable utilizing and tailoring not just the smart spraying system but also all the information services available for arable farming. Thus, the model introduced in Phase III (the smart farming service framework) explicated the FI-enabled service framework, with its specific application (the smart spraying system) detailed at the user interface level. In Phase IV, food chain actors were requested to comment on an integrated model of a smart farming concept provided to them. In the final model, the initial FI-supported smart farming model (introduced in Phase I) was completed according to the results of and elaborations in the different user interventions. The main objective in this ending phase of the project was to get confirmation from the food chain actors that the development of smart farming was heading in a favorable direction.

4.3.5 Example 2: Evaluation of an innovative human-system interface concept called FITNESS

The evaluation of the Functional Integrated Treatments for the Novative Ecological Support System (FITNESS) concept within the MMOtion project is reported in Paper III. FITNESS is an innovative human-system interface concept that was developed at Électricité de France (EDF), originally with the aim of using it in the design of HSI for the control rooms of the N4 reactor type. However, in the end, the FITNESS concept was never deployed in real use for reasons that can only be guessed at, as they remain confidential business decisions and trade secrets. The MMOtion project, however, opened up a possibility to revisit this interesting HSI concept and evaluate the promise the concept may still offer for the process-control work in the project's pilot exercise. The main focus of the pilot exercise was on demonstrating a methodology to support the human factors evaluations of an innovative technical concept. The evaluation methodology selected for piloting was the systems usability case (Koskinen, Laarni, et al., 2021). In the following, it is, however, explained how TiU modeling was applied and used to support the HSI evaluation.

One of the main designers of the FITNESS concept summarized the design philosophy behind it in the following terms: The FITNESS approach draws upon a generalization of the functional representation of the plant, which specifies the purpose of use of the plant functions in each individual situation. This approach enables the complexity of the process to be controlled in various respects. For example, the propagation of function failures from low levels to high functionality levels becomes clearer, which allows the generation of a synthesis of reliable information on the availability of the key functions. In addition, the scheme of operations for commissioning (and decommissioning) the main functions during plant-unit start-up (and shutdown) becomes explicit and the operators are offered the possibility of carrying out related tasks in a more effective yet flexible manner.

The design process and rationale behind the FITNESS HSI concept was also carefully documented. This extensive design documentation covered reports, articles, design meeting records, and personal notes and email exchanges of the designers. However, for the purpose of the pilot exercise evaluation, it was necessary to further specify the innovative features of FITNESS that the expert users (i.e., turbine operators) were expected to experience and report on. TiU modeling was used for this purpose, that is, to create an overall description of the innovative functionalities included in the FITNESS concept. The FITNESS TiU model was created based on the interviews with the aforementioned HSI designer and by familiarizing with the available design documentation. The resulting FITNESS TiU model presented the higher-level functional goals (e.g., the functional tasks of the human operator, the core tasks) in connection with the lower-level physical means (e.g., individual user interface elements and design solutions) and thus allowed viewing how the operators' activities and goals are supported by HSI in their work. Modeling the final FITNESS TiU model (see Table 13) required many iterations and discussions with the designer about how

to formulate the different descriptions so that the central aspects of the FITNESS concept are captured appropriately.

Table 13. The TiU model introduced in the evaluation of the FITNESS concept

FITNESS in process control						
Level 1: Value / core-task functions	Creation of shared awareness – Operators apply the instructions in an intelligent way	Flexibility of acting and reorientation – Operators must be able to take over and adjust the system at any time	Concept mastery and comprehension of wholes – Operators must understand the functioning of the automatic controls – Operators must have a global picture of the process	Interpretativeness of acting – Operators must be capable of identifying the causes and meaning of events	Readiness to act – Operators have responsibility for decision-making and supervision – Operators must be able to detect that an event has occurred	Optimal sharing of efforts – Operators need flexible organization and division of tasks
Level 2: HSI concept requirements	Representation of the plant that is consistent with operators' view of the plant		Components that are grouped into coherent sets and are interconnected	Clearly evident relationships of process events to production or safety objectives		Automation level adapted to operators' needs
HSI concept solutions	1. Functional structure of all kinds of displays		2. Functional structure of synthetic information and alarms (available/unavailable, in service / out of service, and level of degradation)		3. Functional structure and flexible automation of procedures	
Level 3: Interface requirements	Consistency of principles of operation in normal, disturbance and emergency situations	Consistency of dialogs	Consistency of information presentation	Access to synthetic information at all levels	Transparency of the logic of how the system synthesizes information	Freedom in accomplishing tasks and adjusting the level of automation
Interface solutions	Consistency of all operation and interface-management dialogs – The same dialog principles for all plant situations, operation dialogs, and information – Screen structure – Dedicated areas for specific dialogs	Inter-display links – A single operation/ monitoring/ procedure display for each function or component – The same vertical and horizontal structure across all types of displays	Information accumulation – Top-down access and navigation – Bottom-up access and navigation	Presentation of status information – Integration of status information in the displays – Use of animated icons	Procedure system in flowchart format – Functional objective presented for each procedure – Use of animated icons	Functional structure of alarms' processing and presentation – Functional dynamic processing of the on sequences of alarms for each function – Integration of alarms into the displays – Functional synthetic view of alarms for each function

In level 1 of the FITNESS TiU model, the core-task functions are presented (see upmost level in Table 13). Earlier research studies on the work of NPP CR operators were utilized in characterizing the main content of the process control work. The demands of the operator work (that can be considered as defined user requirements) drawn from the FITNESS design documentation (see the bulleted lists in level 1 in Table 13) are thematically organized according to each general core-task beneath the more general core-task function statements.

Even though the FITNESS concept has a computerized HSI connected to the simulator of a 1300 MW pressurized water reactor, for the nuclear process control, it introduces a HSI concept that is very different from conventional HSI solutions. Level 2 (Table 13) depicts the analyzed central HSI concept requirements and HSI concept solutions of FITNESS. The three main concept solutions are: 1) *the functional structure of all kinds of displays*, 2) *the functional structure of synthetic information and alarms*, and 3) *the functional structure and*

flexible automation of procedures. In traditional HSIs, information is often organized according to the logic of process flow diagrams and not so clearly into functional groups and their subfunctions. In the FITNESS concept, functional orientation and structure are pervasive (see Table 13). For example, from the global plant overview display, the operator may navigate downwards to the level of function units (e.g., seawater pumps) from which the operator may move on all the way to the lowest elementary level (e.g., level of individual pumps). In a similar functional vein, the process information and alarms are synthesized and presented corresponding to the function level considered. This approach represents a very new kind of alarm philosophy in which the alarms are presented directly on the process displays and the severity assigned to each specific alarm depends on the functional level at which it is viewed. That is, the severity indication of an alarm takes into account all available redundancies, together with the contextual data of the plant situation, hence assessing the need for the function subject to alarm. This means that at the higher functional levels, there may not be any alarm visible but when moving downwards in the functional display structure, the alarm severity indication may change to yellow or even red (see solution 2 in Figure 20). The concept solution regarding the level of automation was based on the designer's (also a former operator) conception of what automation level would be optimal. Design principles such as that the operator always has the main responsibility for supervising the process and must be able to take over at any time and that the automation should adapt to the needs of the operator and make the operation more efficient drove setting the optimal level of automation for the FITNESS concept.

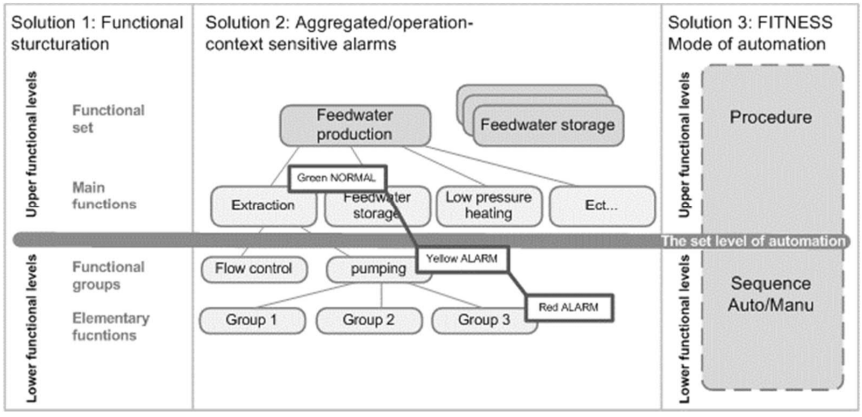

Figure 20. Illustration of the three main concept solutions of the FITNESS concept (Norros et al., 2015)

The FITNESS TiU model highlighted the characteristics of FITNESS that make it distinct from the other HSI concepts utilized in NPP process control. However, for the assessment of the value of the FITNESS concept, more operating experiences and investigations of different aspects of the concept were required, which made it an ideal candidate for demonstrating a methodology for human factors evaluation of innovative human-system interfaces.

The TiU model in planning human factors evaluation

The FITNESS TiU model was central in the planning of the evaluation. The content of the FITNESS TiU model provided a clear focus for the evaluation, as in the model the main concept solutions of FITNESS are made explicit and documented in detail. FITNESS evaluation utilized a human factors evaluation approach called systems usability case (SUC). SUC is based on safety case thinking and the notion of systems usability (SU). SUC is constructed through three basic elements, that is, claim, argument and evidence. In forming the claims about the value of the system under evaluation, an understanding of the design rationale is essential. TiU modeling enabled the creation of an overall view of the object of evaluation in a very condensed form. In the case of the evaluation of the promise of FITNESS, three types of claims were the most relevant to address:

- A particular HSI concept solution supports fulfilling certain work demands (core-task functions),
- A particular interface solution concretizes the HSI concept solutions, and
- A particular interface solution supports meeting certain work demands.

Following these basic claim structures, for example, a claim could be made that "the functional structure of alarm processing and presentation (interface solution) supports/enables interpretativeness of acting (core-task function)." The above type of claim is related to the expert users' point of view, as the interest is in the tool's capability to evoke positive user experiences and provide value for the work. The claims about the FITNESS concept generated based on the FITNESS TiU model were then used for further planning of the evaluation. Prior to the actual evaluation occasion, it was necessary to define the content of the scenario runs, frame the questions and prepare all the other supporting evaluation material. All of this preparatory work focused on the specifics of the three main HSI concept solutions stated in the FITNESS TiU model. For example, the scenario runs (altogether five scenarios) were developed under the three particular themes, that is to say: I) functional information presentation and FITNESS mode, II) synthesis of plant state and alarm and, III) functional information presentation and different operation modes that were closely related to the three identified concept solutions. Paper 3, included in this dissertation, contains a detailed account of aspects such as scenario planning and presents the prepared pictorial material.

The TiU model in training of operators

In the FITNESS evaluation, the first day was reserved for the training of the operators (Table 14). Even though the designer of the FITNESS concept had developed a dedicated training manual for FITNESS, the training of operators for the evaluation was refined and modified to highlight the specific characteristics of the concept identified in FITNESS TiU modeling.

Table 14. The organization of the FITNESS evaluation's training day

Day 1: Training	
Topic	**Format**
The goals of the design/evaluation experiment	Presentation by the MMOtion human factors specialist
The principles of the FITNESS simulator and HSI functions	Presentation by the designer
Testing FITNESS and the different HSI functions	Free exploration and assistance when needed
Closing discussion and first user experiences	Group discussion (all parties)

Especially the closing discussion of the training day was designed based on the FITNESS TiU model. The three innovative concept solutions were reviewed to assess how they materialized in the interface. The first impressions and user experiences were carefully recorded and used as evidence in constructing the SUC.

The TiU model in human factors evaluation and analysis of results

In constructing the SUC, the description of the different solutions integrated into the proposed new system is not readily made explicit. TiU modeling instead aims to discover and explicate the innovative features of the tool and describe and organize them in relation to the demands of the work activity under development. In the FITNESS evaluation, the TiU model made it possible to focus the evaluation on the identified key innovative features that were claimed to improve the efficiency and safety of the process control work. For example, more elaborated discussions (e.g., in the focus group discussion) with the operators about the content of the FITNESS concept in the course of the evaluation could be held, thanks to which more detailed evidence was gained about the value of the concept. A short summary of the findings of the FITNESS evaluation is provided below (see Table 15). The detailed account of the results of the evaluation is presented in Paper 3.

Table 15. The organization of the FITNESS evaluation's training day

HSI concept solutions	1. Functional structure of all kinds of displays	2. Functional structure of synthetic information and alarms (available/unavailable, in service/out of service, and level of degradation)	3. Functional structure and flexible automation of procedures
Promise	It was experienced that the functional structure provided a good presentation of the facility. In addition, the operators thought it aided in understanding the logic of the system and the interdependencies within the functional levels. The interface solutions were seen to effectively capture the functional structure, e.g., in inter-display links and in the consistency of all operation and interface management dialogs. However, one criticized issue was the navigation within the hierarchical display system.	This feature received the least confirmatory evidence. One reason for this may be the fact that this was the most radical innovative feature of the FITNESS concept that the operators had no previous experience with. The operators had trouble in reading symbols and understanding their connection to the severity index determined by the current view of the display hierarchy. Moreover, it was not always clear to the operators which functional level they were at, which is key to understanding the severity of the emerged issue. However, it was promising that the solution was positively linked with the requirement that the relations of process events to the achievement of safety objectives must be made evident. Therefore, it might be that the concept solution itself is worthwhile investigating further if some other interface solution could materialize it in a more appropriate form.	This feature was experienced most positively (and gained the most supportive evidence). The operators thought that the solution was well manifested in the interface by the procedure system in a flowchart format. It was also found to support the requirement that level of automation must be adapted to operator needs. The so-called FITNESS operating mode was experienced to support flexibility of operation and optimal sharing of efforts leading to, e.g., reducing the operator workload in some demanding operational situations. Some concerns were raised concerning the acquisition of expertise and a certain passivity that may be caused by operation in automatic sequence.

4.4 Summary of the results and answers to the research questions

In this subsection, the results are summarized and concise answers to the research questions are given.

Sub-question 1 concerning the present status of the participatory design practices and user involvement in safety-critical system design led to the review of a number of studies addressing the topic. The resulting understanding of the current participatory practices within safety-critical system design was not very favorable. Even though a lot of academic research was carried out, the learnings and insights of these studies have not been incorporated into well-established industry practices. There was a lack of responsible HF specialists and organizational structures as well as integrated design processes and methodological repertoires that could be used for involving relevant user groups.

In the development of safety-critical systems, the human and social aspects are essential in achieving safe and resilient design solutions. For that reason, the human factors efforts within safety-critical system design need to be systematic and addressed at all levels of system engineering (i.e., organization, process, and product) and throughout the design. It was proposed that a tailored HFE program should be established in the safety-critical system design project to facilitate the implementation of HF activities that appropriately address the design task from multiple viewpoints and abstraction levels as well as acknowledge the needs and preferences of relevant user groups. In the contextually defined and tailored HFE program, elaborating the points of user interaction would be especially important in order to facilitate participatory processes and active user involvement in design.

The sub-question 2 concerned the use of functional models to facilitate expert users' reflection on work. Based on theoretical considerations about the mediating role of technology in activity and the practical problems of addressing this appropriately in design led to the introduction of Tools-in-Use modeling providing a functional conceptualization of the work. In Tools-in-Use modeling, both the work activity and the emerging new tool are embodied. The content of the TiU model is always contextually defined and starts from comprehending the work activity to whose successful performance the new tool aims to contribute. The work activity is expressed in the TiU model in the form of core-task functions that reflect the central content of the work domain. This is followed by the description of the emerging tool regarding the concept and the interface level requirements and solutions. By constructing these two points of view – that is, the generalization of the work activity and the developed technology concept – a condensed and tangible description of the proposed new design from functional point of view can be created.

Sub-question 3 dealt with the question of what kinds of contributions the expert users can deliver for safety-critical system design in different phases of the product lifecycle. Based on the review of the related research and the practical research work on different cases included in this thesis, the expert users' knowledge contribution to safety-critical system design may be extensive and

certainly goes beyond participating in traditional usability evaluations as a subject. The expert users have in-depth knowledge and insights on how the safety-critical system can or cannot be used and their subjective experiences may reveal aspects concerning the suitability and potential of the proposed design solutions. In the early stages of design, the expert users can 1) set requirements for the development of the future system through their contextual and operative knowledge. These past experiences enable the expert users to 2) envision future possibilities in such a way that they still correspond to the practicalities of everyday work and thus have a bigger potential to develop a meaningful tool in work. The users who operate safety-critical systems might themselves have difficulties grasping the possible implications that the introduction of a new tool will have, not to mention persons without operational expertise. Therefore, the ability of operators to 3) critically reflect on the fulfillment of the requirements should be exploited in design. User involvement and their knowledge contribution would have the greatest impact when integrated into the design in the early phases when there is still room for alterations and formative design feedback.

The main research question of this thesis asked how can participatory methods for expert user reflection on work be furthered to better integrate human and social considerations in safety-critical system design. The Tool-in-Use model draws on the description of the domain-specific critical features of the work while advancing the foreseeing of promise the future activity (the second function in CTD design model).

The modeling of the TiU facilitates the focus on the safety-critical work activity, yet allows for the free exploration of the different characteristics of the proposed new tool and discussion of their potential to support the core task functions. Consequently, enabling the expert users both exploring and evaluating individual task demands and future development prospects of the tools in a way that other available participatory methods have not been able to address. The TiU model enables displaying together the main ingredients of both worlds, that is, the central functional content of expert users' work and the problem solutions space that the designers are used to working with. Thus, in doing so, the TiU model establishes a fruitful ground for participatory processes and from which to start collaboratively developing the future system.

5. Discussion

In this thesis, the TiU modeling approach is presented as most important methodological contribution that complements the other prevailing participatory

methods aimed at addressing usage activity and involving expert users in design. In this chapter, the results of the research work are reflected on and the findings discussed in relation to the previous research and what kinds of practical implications the findings may have.

5.1 Advancing participatory processes in safety-critical system design

A safety-critical work system at its fundamental level represents a design task of a magnitude and complexity that no single design engineer could complete alone. Therefore, safety-critical system design is a collaborative activity in which representatives of several highly specialized fields of engineering participate (Lu et al., 2007). Human factors is a design discipline that aims at contributing to the system design particularly by promoting a profound contextual understanding and incorporating the usage point of view into design decisions.

However, I have more than once read in magazines or experienced in my own research studies that expert users feel that the proposed design solutions do not fit the realities of their everyday work. Even if a design solution is technically solid, the users might find it awkward. For example, when doing field observations and interviews in the process industry, a process operator once explained to me that the operators did not want to use a new automatic start-up functionality because they found it very slow and thought that they could do the same procedure manually much more quickly and efficiently. Later, when discussing this with the designer, I heard that this functionality was also designed to optimize and take into account other aspects of the system such as the durability of the technical equipment, and that was why more time was reserved for some steps of the start-up procedure so that, for example, optimal temperature for equipment durability would be reached. However, the users did not seem to be aware of this and they found the new automatic function useless. Clearly, this issue could have been avoided in operation by, for example, providing more training or just explaining better the design rationale of the new functionality to the operators. Another similar example can be found in the operation of heavy machinery: I was told that the operators often needed to override the set safety limits to manage one specific operational situation. Again, I wondered why this particular operational situation was not acknowledged better in the design so that the users would not need to purposely override the safety functions.

The above are practical examples of the problems of incorporating appropriate human and social understanding into design projects. Similar problems were also identified in the reviewed literature, revealing that the impact of human factors is still not integrated to its full potential in the design of safety-critical systems (Balfour et al., 2012; Money et al., 2011). One issue that might affect this is that human factors in the context of safety-critical systems have focused on V&V and especially on summative evaluation at the later stages of design (e.g., ISV). This evaluation phase has perhaps also received the most attention in the regulatory procedures and guidelines under which the new system must be formally assessed before it can be commissioned. Conducting human factors

evaluations of safety-critical systems such as NPP control rooms is not a straightforward task to accomplish and thus demands methodical development efforts from the human factors community (Braarud & Strand, 2011; O'Hara, 2009; Savioja, 2014a; E. Simonsen, 2018).

Without wishing to diminish those achievements regarding the human factors evaluations at all, some of the HF issues identified in these later evaluation phases would benefit from formative evaluation and would have been most efficiently tackled when the requirements for the new system were set at the beginning of the design process. Several authors have discussed the benefits of formative evaluation and suggested that human factors should take a more active role in early evaluations (Boring et al., 2015c; Norros, 2014; E. Simonsen et al., 2020). For example, Simonsen has suggested a combination of heuristic evaluation and scenario-based talk-through methods for performing formative control room system evaluations (E. Simonsen, 2018). Boring et al. (Boring et al., 2015c) discussed the importance of integrating the operators' knowledge into design at early stages of development and used the terms pre-formative epistemiation and formative epistemiation for this purpose. According to him, pre-formative epistemiation may happen prior to the actual design phase by means of, for example, a cognitive walkthrough procedure used in support of a task analysis with the aim of capturing operator needs and expectations for the system.

Recently, Boring et al. (Alivisatos et al., 2021; Boring, Ulrich, & Lew, 2021; Boring, Ulrich, Lew, et al., 2021) have suggested a control system design prototyping toolkit – which they call the Rancor Microworld – that can be used for rapid design and implementation of prototype control systems and accompanying human-machine interfaces, thereby yielding design input early on in the new reactor development process. These abovementioned research studies have also recognized the gap in today's design and evaluation practices: the need to commit human factors earlier on in design and conduct assessments with formative purposes for the new design solutions.

The purpose of this thesis was to enhance the understanding of human factors contributing to safety-critical system design and especially to promote methods and processes that would allow expert users to get involved in design in a way that can be utilized to deduce design implications and improve the proposed design solution. Regarding the temporal dimension of the design, this thesis aims to support and reassert the inclusion of expert users' operative knowledge in the early stages of the development process. Thus, the results of this thesis contribute to the development of human factors as a design discipline and foremost by advancing participatory processes and expert user involvement early in the design process.

5.2 Methodical implications

The form in which the emerging design solution may be presented affects the expert users' involvement and their evaluations. Most often, operators in the NPP context participate in human factors evaluations conducted in a variety of

simulator environments (e.g., development or training simulators). In this kind of simulator setup, the operators may already experience the design solution in quite concrete terms. In the simulator runs, the operators are invited to attend to the handling of a certain operational situation such as a process disturbance that may already give tangible experience about the functioning of the design solution. Other methods typically used to present the design solution according to the reviewed literature were different kinds of mock-ups and prototypes of various levels of maturity. These are useful as they can be produced with relatively low investments and still give the design solution a tangible form that can be discussed and reviewed collaboratively.

The TiU modeling approach presented as one concrete result of this thesis complements the other prevailing participatory methods (e.g., prototyping and scenario-based approaches) aimed at addressing usage activity and involving expert users in design. The TiU model aims to make the emerging design solution tangible in an illustrative way by including a concise description of the basic solutions that the new tool design is constructed from. The method contributes to conducting qualitative analysis of work so that an informed and constructive discussion can be held about how the design solutions support the work demands. The TiU modeling approach is developed particularly with expert user involvement in mind and with the idea of making the design solution explicit so that the users can start comprehending the potential value that the solution may introduce into their object of activity. Thus, in CTD (see Figure 2), TiU modeling first and foremost serves to foresee the promise of the design function.

Many potential benefits can be seen in the use of TiU models. As the TiU model makes the work activity explicit by describing the core-task functions, the work activity is constantly present in design and can be referred to at any time even though the discussion would be about some specific characteristic of the design solution. Even though the design project in question would be in the summative evaluation phase, constructing the TiU model would involve the design parties starting from the functional content of the work activity in a way consistent with the basic ideas of human-centered design and understanding the contextual needs and preferences of users.

Secondly, the content of the TiU model is collaboratively constructed starting from the analysis of the work tasks and then proceeding to the description of the design solution at both its concept level and its user interface level. Thus, the design participants can begin to foresee step-by-step the promise of the proposed design solution for the work. The core-task functions are exposed to the expert users' review, and they are taken into active contemplation. Thus, the users can be actively involved in the design process from the beginning, even before any potential design solutions are considered. Arguably, constructing TiU models demands more thorough analysis of the work activity, and when used for facilitating participatory processes the expert users are also engaged in reflecting on and analyzing their work.

Constructing the TiU model is an iterative process within which the participants can explain their viewpoints, relate what the others have brought to the discussion and talk about their own experiences. The different aspects of the

TiU model can be critically questioned and reflected in the design process. The conflicting viewpoints of participants may be easier to discuss when the design rationale and the characteristics of the design solution are explicitly stated and visible to all. On the other hand, the threshold for giving feedback may be lower when the design solution does not as yet seem to have a very mature form, that is to say, a functioning prototype or full-scale simulator. Consequently, TiU models may facilitate and encourage expert users to voice their opinions. It does not take too much effort to adjust or make changes to a TiU model, and yet the impact on the overall concept may be radical (like in the case of the introduction of the smart farming framework in Paper 4).

Moreover, as TiU models are collaboratively constructed, the participants are in control of knowledge creation within the modeling process and share ownership of the final outcome (i.e., a vision of a meaningful and promising future). It is likely that each member of the design team can make a meaningful contribution to the TiU model as it has elements from both worlds, that is, the operation of the system (core task) and the design engineering of the system (requirements–solution structure). On the other hand, it is unlikely that an individual can alone complete TiU modeling in such a way that it would appropriately express all the aspects it includes (i.e., the work task, the concept, and the interface level). Consequently, TiU inherently builds on collaboration in completing the modeling.

The description in the TiU model proceeds logically from the abstract generalization of the work tasks and the concept to the concrete description of the interface elements. The TiU model facilitates moving between the different levels of abstraction and seeing how the different levels are interrelated. Thus, the TiU model enables an illustrative description of the new design solution for future work in a more generic and conceptual form as well as facilitates comprehension of the interrelations of the work system. TiU provides a kind of representation of the joint human-technology system and allows examining how the targeted functionality may be achieved as a joint effort of the different parts of the system.

5.3 Practical implications

The fact that the involved users are expert users may affect the choice of suitable participatory methods and processes. Moreover, the design objective (e.g., focus on an individual interface or task or on a full-scale control room modernization) may need to be considered in the form and extent of user involvement.

It has been seen necessary to improve and develop safety-critical design practice – and in particular like this thesis to advance the collaborative and participatory processes (including expert user involvement) in order to reach integrated design solutions. The research studies presented in Paper 1 and 2 showed that formative design feedback can be reached already with low-fidelity design-solution representations. Tools-in-Use modeling in its simplest form produces a low-fidelity representation of the proposed design solution but in a way that also makes the work activity explicit (unlike traditional prototypes). A concrete

description of the TiU modeling approach is provided and it may be used in a variety of contexts as demonstrated in the studies presented in Paper 3 (i.e., NPP context) and 4 (i.e., pesticide spraying context).

I envision the TiU modeling being a participatory design artefact used in the research and product development context of safety-critical systems. Thus, the primary users of the modeling approach would be designers and developers of the systems and in particular the persons being responsible for inclusion of the human and social aspects in the design process, that is, the human factors experts and HSI designers. Applying the TiU does not demand unreasonable amount of training or specialized knowledge beyond understanding its construction logic (i.e., proceeding from the functional usage value level of the system to the concrete interface solutions). I recognize that presumably the value level is the most challenging part of the TiU model to commit to (at least from the traditional system engineering organization point of view), however, difficulties in this may already help the design organization to recognize their absent methodical repertoire regarding analysis of the human activity and initiate some positive developments to this aspect. Iterating the content of the other two levels (i.e., concept and interface) is most likely much more straightforward at least for the system developers.

Based on my experiences of working with TiU modeling, it can be to a certain degree completed by an individual (e.g., designer) but collaboration is soon needed to elaborate further on the different aspects of the model. Arguably, TiU modeling may cost-efficiently reveal if some part of the design rationale from the work activity point of view is incomplete or weakly understood and justified. At the beginning of the design process, it is especially important to support shared awareness and exchange of ideas. The TiU model may provide one design tool to initiate discussing and seeing how the different parts are related to each other and what kinds of design decisions lie ahead and should be made to reach an integrated design solution.

One aspect of the design of safety-critical systems and involvement of expert users is that access to relevant user groups and expert users is often restricted. It may be that the number of expert users operating one system is not very high and the operation of the process is continuous, leaving little room for other activities such as participation in innovative processes. Therefore, there is a need for methods that may produce qualitative descriptions with the involvement of fewer expert users instead of relying on quantitative processing of user data and a large number of involved expert users. As the expert users may be busily occupied with their everyday work activities and may not have any training on design, supporting their participation in the design process is especially important. TiU models invite the expert users to foresee the new design ideas but at the same time emphasize their role and expertise that is of importance for the success of the development process, which may provide extra motivation for the users to participate and share their operative knowledge. For the primary users of the TiU models, that is, the human factors experts the model provide a con-

cise structure to help the expert users to start foreseeing and discuss the different aspects of the emerging design solution and thus facilitate mediating their operative expert knowledge between the design and usage organizations.

5.4 Limitations of the research work and suggestions for future research

The research conducted in this thesis may have been improved in many ways and the achieved results could be developed further.

One frequent complaint regarding the more extensive adoption and utilization of HF methods, as also proposed in this thesis, is that they are laborious and demand highly specialized methodological knowledge. It is true that acquiring the contextual information, for example, to model the core-task functions of a specific work requires efforts and resources. Moreover, the input of only human factors specialists is not enough; time and contributions are also needed from representatives (e.g., operators) of the specific domain being modeled. For example, in modeling the core-task functions, interviews and discussions with expert users are often needed. In addition, transforming these empirical enquiries into design implications or a clearly defined set of specifications for the new design solution is not a straightforward task, either. However, considering the nature of the systems that are in focus – that is to say, safety-critical systems – I feel that a certain rigorousness is necessary, as the success of the design can have consequences beyond the well-being of individual workers. Moreover, as these systems are complex and large in size, careful analysis and domain knowledge are needed in order to specify the real development needs at which the limited resources should be directed.

Tools-in-Use modeling and the participatory processes initiated around it may also be further developed. I have attempted to provide a flexible method that could be adopted throughout the design process and regardless of the starting point of a specific project (e.g., identification of development needs or summative evaluation of a design solution). More experiences of how the model works in different phases of design would facilitate its development. One specific phase that the TiU model is still not used in is performance monitoring and collecting operating experiences (O'Hara et al., 2008) when the new system is commissioned and taken into use. I think the modeling approach would have potential to classify the operating experiences according to the different characteristics of the design solution and the core-task functions and thus help identify potentially emerging HF issues in a more proactive manner. In the research studies included in this thesis, the modeling approach was mostly utilized in interacting with expert users; however, how the model may be used for involving different user groups (e.g., passengers of an automatic tram) in design should be further explored as well. TiU modeling requires input and contributions from both expert users and design engineers. The focus in this thesis has been on the involvement of expert users and less on how the designers may use the model to support their design thinking and the practical design work in developing the solutions; this would thus be one aspect to study further.

5.5 Conclusions

In this thesis, I have presented research related to user involvement in safety-critical system design. The main motivation has been to advance the design of high-quality tools that are useful and support efficient and safe operation of systems. Particularly, the inclusion of the valuable operative knowledge of expert users in the design of safety-critical systems was pursued.

For this purpose, a functional modeling approach called Tools-in-Use was introduced. By constructing the TiU model, it is possible to view the new design solution (i.e., tool) from the work activity (i.e., core tasks) point of view in an illustrative way and engage expert users in discussion about the value and meaningfulness of the proposed design.

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Designing tools for performing safety-critical tasks is demanding engineering discipline. Numerous specialized engineering knowledge needs to be integrated to create a well-functioning solution that appropriately serves carrying out the work and fulfilling the goals of the activity.

Expert users are a group of specialists that could potentially contribute much to developing the appropriate solutions. However, in the context of safety-critical system design, their role has conventionally been restricted to involving them in the later evaluation phases, thus, leaving much room to extend their role in design.This thesis aims to promote early expert user involvement and thus enable better inclusion of their hands-on experience and wealth of operative knowledge in design.

A Tools-in-Use (TiU) model is introduced that may facilitate participative processes and enable constructive designer - user interaction and discussion about the different aspects of the emerging design solution. The article-based thesis consists of six publications and an introduction with review of literature, providing new knowledge that makes a methodical contribution to expert user involvement in safety-critical system design.

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