Scalable Human Computer Interaction in Control Rooms as Pervasive Computing Environments

Nadine Flegel
N.Flegel@hochschule-trier.de
Trier University of Applied Sciences
Trier, Germany

Kristof Van Laerhoven
kvl@eti.uni-siegen.de
University of Siegen
Siegen, Germany

Tilo Mentler
T.Mentler@hochschule-trier.de
Trier University of Applied Sciences
Trier, Germany

ABSTRACT

Private and professional life contexts must be viewed as pervasive computing environments, with the aim to address peoples' needs and tasks as well as cooperation and communication issues. However, there is a risk, that this results in handling a growing number of devices and complex interactions. The question arises to what extent interaction concepts that were designed for single or a few devices can be transferred to such environments. This can be seen as a scaling problem in terms of cognitive ergonomics. This is also an important issue in safety-critical domains, where control rooms serve as central units, as the demands on operators are increasing. Support is needed in decision-making, communication and collaboration. This paper describes the research questions and methodology of the development of design principles for scalable interaction design in control rooms from a cognitive ergonomics perspective. The expected outcome is a set of concepts that are specifically suited for safety-critical pervasive computing environments.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Scalability, Safety-Critical Systems, Control Rooms, Interaction Design Patterns, Pervasive Computing Environment

ACM Reference Format:
Nadine Flegel, Kristof Van Laerhoven, and Tilo Mentler. 2022. Scalable Human Computer Interaction in Control Rooms as Pervasive Computing Environments. In *33rd European Conference on Cognitive Ergonomics (ECCE 2022), October 4–7, 2022, Kaiserslautern, Germany*. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3552327.3552351

1 INTRODUCTION

Increasingly, private and professional life contexts must be viewed as pervasive computing environments where "people and devices are mobile and use various wireless networking technologies to discover and access services and devices in their vicinity" [19]. The aim is to address peoples' needs and tasks as well as cooperation and communication issues. However, there is a risk, that this results in handling a growing number of devices and complex interactions [23]. The question arises to what extent interaction concepts that were designed for single or a few devices can be transferred or adapted to such environments. This can be seen as a scaling problem in terms of (cognitive) ergonomics.

In terms of smart control rooms [18] or control rooms as pervasive computing environments [8] this challenge is also being addressed in safety-critical domains where control rooms are "location[s] designed for an entity to be in control of a process" [10], e.g., fire and rescue services, public utilities, and cockpits (e.g., ship bridge, aircraft). Operators' task are to monitor and control the state of a highly complex system and to restore it in case of deviations, which is an extremely demanding activity (e.g., stressful conditions, decision-making within short time periods). These demands will become even more stringent in the future, as the tasks and responsibilities of control room operators in many domains grow (e.g., low-voltage power grids in energy supply, deployments in larger jurisdictions for rescue services).

In my PhD, I follow the approach of human-centered control rooms as pervasive computing environments [8]. After presenting the background concepts and related research in which my research is situated, I will introduce the research questions and methodology and give insights into preliminary results.

The expected outcome of this work is a set of scalable interaction design concepts, which can be used safely and efficiently by technology experts depending on the application context in future pervasive computing environments with a variety of interactive objects (e.g., mobiles, wearables, sensors, various displays, mixed reality). These concepts are expected to have application potential beyond control rooms, in various other safety-critical domains, for instance in healthcare for surgeons in an operating room.

2 BACKGROUND AND RELATED WORK

2.1 Control Rooms from a HCI Perspective

Control rooms have been discussed for over 30 years in HCI, Human Factors (HF) and (Cognitive) Ergonomics [13, 16, 21]. State-of-the-art control rooms are equipped with a variety of input and output devices in the form of stationary individual workstations with several displays, shared public screens and multimodal alarm systems [18] that support situation and group awareness to a certain degree. Current research towards novel control room environments considers a multitude of specific functionality approaches, e.g., touch interaction for surfaces, gesture and voice control at workstations, gaze-based mouse interaction at multi-monitor workstations [7]. More sophisticated approaches for computer-supported cooperative work like multi-touch tables [12] have not been deployed

ECCE 2022, October 4–7, 2022, Kaiserslautern, Germany

ACM ISBN 978-1-4503-9808-4/22/10.
https://doi.org/10.1145/3552327.3552351

widely yet. Scalability has only been considered at the sidelines of the aforementioned research so far. Jetter et al. [11] describe, among others, a power-versus-reality-tradeoff in blended interaction design stating that user interfaces which take well-known real-world concepts into account to a great extent, are often inferior to hard-to-learn user interfaces in various aspects (e.g. versatility and scalability). Limiting their research on gesture and voice control to a single display workplace in a control room setting, Heimonen et al. [9] state that multimodal interaction for a multi-display system requires further research.

2.2 Scalability from a HCI Perspective

The term "scalability" is used to describe various challenges in HCI with respect to all phases of human-centered design (the "analyze-design-build-evaluate-cycle" [3]). According to Brown et al. [2] scaling issues exist in ergonomic HCI methods with respect to the number of users, the multitude and complexity of systems and the different contexts of use.

- **Analyze:** Gathering feedback from users [14] or issues with common task models for complex systems [15].
- **Design:** Challenges in user interface design are for instance the visualization of big data [24].
- **Build:** User interfaces that can cope not only conceptually but also in terms of programming with the requirements of many users, large amounts of data, many different end devices, etc. [24].
- **Evaluate:** Duration of studies and evaluations, which are often feasible only for short spans of time [2]; Difficulties (especially in safety-critical domains) to carry out evaluations in real operation. Alternative solutions must be found to test as realistically as possible [5].

A definition of scalability that is in line with the introduced issue of this work (section 1), is the challenge of handling a growing number of devices and resulting interactions within a specific environment (here: control rooms), which has been defined as "localized scalability": "good system design has to achieve scalability by severely reducing interactions between distant entities" [23]. What is missing are concrete design principles for the realisation of localized scalability as well as specific interaction design concepts for scalability with respect to workflow-, task-, & goal-oriented solutions.

3 RESEARCH QUESTIONS

The research questions of this work are examined on the example of three different control room domains in order to compare the results across different domains. Control rooms can be distinguished according to several aspects, the taxonomy of Mentler et al. [17] classifies control rooms with respect to the location and number of operators working in parallel. According to this taxonomy two domains with "fixed" control room locations were chosen (control rooms in fire and rescue services; energy control rooms in public utilities) as well as a domain with a "mobile" control room (ship bridges in maritime traffic). The research questions are as follows:

- **RQ1:** What design principles exist for scalability from the perspective of human-computer interaction?
- **RQ2:** What are the characteristic properties of control rooms?
- **RQ3:** To what extent are the researched design principles suitable in control rooms?
- **RQ4:** How can characteristics of control rooms be taken into account in scalable human-computer interaction?
- **RQ5:** Which of the researched design principles are most suitable for typical use scenarios?
- **RQ6:** How well do the selected design principles work in control rooms in terms of feasibility, usability and user experience (autonomy of control room operators vs. contribution to the safety of the process)?

The research questions RQ5 & RQ6 will be examined on three typical use scenarios (one in each control room domain). These will be defined in the analysis phase of this work (see section 4).

4 METHOD

Research follows a human-centered design process of five iteratively progressed phases (see Figure 1).

Phase 1 will be guided on the following questions: What kind of approaches already exist in HCI (especially in safety-critical domains)? What is the focus of these approaches and what relation do they have to scalability? In phase 2, similarities and differences of three control room domains (see section 3) will be identified in terms of users' needs, tasks, cooperation, working environment and organisation. This will be done by an ergonomic analysis, in which field studies (contextual inquiries lasting several days), interviews and online surveys will be conducted with experts from the field of safety-critical HCI/HF and control rooms. Three typical use scenarios in the respective domains will be derived. The aim of phase 3 is to derive design patterns from RQ1, RQ2 & RQ3 for scalable interaction design in control rooms. They are "proven solution[s] to [. . .] recurring design problem[s]" [1], and "a format for capturing and sharing design knowledge" [4]. These patterns will be based on tasks, workflows and operators' needs with respect to daily routine and critical situations, different levels of automation as well as individual and cooperative work. A strict methodology is followed to gather and select design patterns, following an evolution process with feedback loops (e.g., workshops, interviews, surveys) where the patterns pass different states [22]. The aim of phase 4 is to develop a concept for selected design principles and to implement it in an ergonomic perspective with as minimal/ unobtrusive technology as possible. This will be done in the first step as a prototype with the help of a wearable framework (see Figure 2).

In phase 5 prototyping and evaluations will be carried out in a realistic and controlled control room laboratory environment, in a multiplayer virtual reality simulation, in cooperation with professional operators, domain experts and HCI/HF experts in order to ensure stable, replicable testing conditions as well as practice-oriented results. The summative evaluation will be conducted as an A/B test in which participants perform specific tasks with and without the support of the prototype, to evaluate with regard to usability and user experience. In addition, the transferability to other safety-critical domains (e.g. surgeons, working in an operating room) could be tested in this phase.

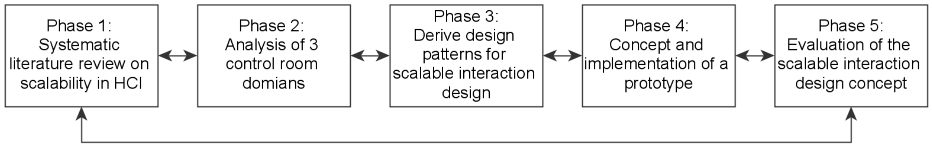

Figure 1: Phases of this work.

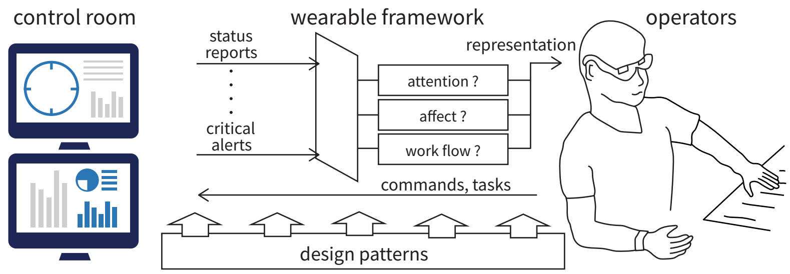

Figure 2: Modelling operators' cognitive load and affective state on a wearable to influence information flow and representations guided by design patterns

5 RESEARCH TO DATE AND FUTURE WORK

The systematic literature review (phase 1) is ongoing (see section 2.2). In order to gain an understanding of the socio-technical system and to derive solutions, the methods described subsequently were applied in phases 2 and 3.

At first, a root concept for control rooms as pervasive computing environments was developed [8]. This includes the vision of a control room which is aware of people and processes and the starting assumption that the operators' cognitive load & affective states are assessable and activities & workflows can be modeled and identified (see Figure 2).

Semi-structured interviews with 9 control room operators and researchers on HCI and HF in safety-critical systems were conducted [8]. These highlighted potentials (e.g., a flexible way of working could have a positive impact on health and cooperation efforts) but also challenges of the previously mentioned vision. Measuring cognitive load and gaining acceptance are two of them. Operators expressed potential for this to contribute to the safety of the process, but at the same time they were concerned about feeling monitored in terms of what is recorded and who has access to it. This raises the question of how to create transparency and acceptance, for instance through visualisation of recorded data.

Two workshops were conducted in-person with operators in one fire and rescue service control room (n=3) and one energy control room (n=2). In order to gain a comprehensive understanding of the socio-technical system, questions were asked according to the POISE (People, Organisation, Interactive System, Environment) framework [20]. The vision of control rooms as human-centered pervasive computing environments was discussed on the example of different scenarios, e.g., autonomously carries out identified tasks, filters messages and forwards them to other operators if an operator is busy or stressed at the time, ensures that a message reaches the operator or suggests actions to maintain the operator's health. These were discussed according to autonomy and acceptance of operators and the contribution to safety of the process. From the results, it can be concluded that the operators are basically positive and open-minded about the vision and see potential, as they address everyday problems. However, it is important to mention that the aforementioned challenges and concerns during the expert interviews were also expressed.

In parallel, an online-survey on digitalization in control rooms with operators of the three selected control room domains (section 3) was conducted (n=163). Control rooms as pervasive computing environments were introduced with the same scenarios as discussed in interviews and workshops. In general, the results showed that control room operators have a quite high affinity for interacting with technology. However, it can be cautiously deduced that the operators of a ship's bridge are more critical of the scenarios and see less to no added value in some scenarios.

In addition, UX aspects in control rooms were investigated with the workshop groups and participants of 4 follow-up interviews from the survey, using the interaction vocabulary by [6] and a description of the respective group with terms that apply to an "ideal control room". The findings were that control rooms must first and foremost be safe, fast, stable and reliable, but should also have a certain "high feel-good factor".

About 40 design patterns have been derived from the analysis phase and adapted from a literature review on software engineering patterns for scalability. Pattern cards were chosen as a form of presentation reminiscent of playing cards. Two candidate patterns are shown in Figure 3. A reoccurring problem of the Load & State Balancer is that information is provided to many operators at the same time ignoring their current workload or affective state. Modelling these aspects (stress in particular) could be a solution, to distribute

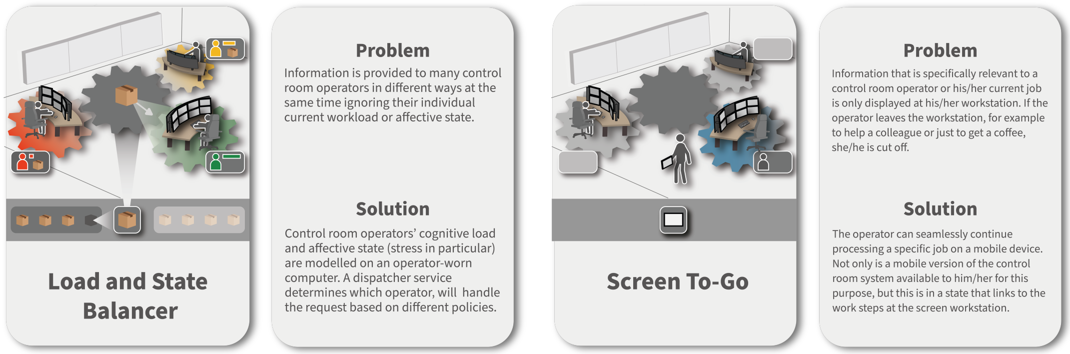

Figure 3: Excerpt of design pattern cards for scalable interaction design in future control rooms.

tasks and information based on different policies. Another pattern is Screen To-Go. In state-of-the-art control rooms, operators are tied to their workstations to receive information and execute tasks. Supporting a flexible and seamless way of working with a mobile device could provide a solution.

The design patterns will be tested with other domain experts and control room staff for comprehensibility and practicality. For this purpose, the pattern cards will be printed as tangible elements in playing card format, as well as being made available in a web-based information system with a feedback function. Finally, they will be incorporated into the realization of the wearable framework for control room operators in phase 4, and will be evaluated in phase 5.

ACKNOWLEDGMENTS

This project is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 425868829 and is part of Priority Program SPP2199 Scalable Interaction Paradigms for Pervasive Computing Environments.

REFERENCES

[1] Jan O. Borchers. 2008. A Pattern Approach to Interaction Design. In *Cognition, Communication and Interaction: Transdisciplinary Perspectives on Interactive Technology*, Satinder Gill (Ed.). Springer London, London, 114–131. https://doi.org/10.1007/978-1-84628-927-9_7

[2] Barry Brown, Susanne Bødker, and Kristina Höök. 2017. Does HCI Scale? Scale Hacking and the Relevance of HCI. *Interactions* 24, 5 (2017), 6 pages.

[3] Keith A. Butler. 1996. Usability Engineering Turns 10. *Interactions* 3, 1 (jan 1996), 58–75. https://doi.org/10.1145/223500.223513

[4] Eric S. Chung, Jason I. Hong, James Lin, Madhu K. Prabaker, James A. Landay, and Alan L. Liu. 2004. Development and Evaluation of Emerging Design Patterns for Ubiquitous Computing. In *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques* (Cambridge, MA, USA) *(DIS '04)*. Association for Computing Machinery, New York, NY, USA, 233–242. https://doi.org/10.1145/1013115.1013148

[5] Mark Colley, Marcel Walch, and Enrico Rukzio. 2020. Unveiling the Lack of Scalability in Research on External Communication of Autonomous Vehicles. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382865

[6] Sarah Diefenbach, Eva Lenz, and Marc Hassenzahl. 2013. An Interaction Vocabulary. Describing the How of Interaction.. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (Paris, France) *(CHI EA '13)*. Association for Computing Machinery, New York, NY, USA, 607–612.

[7] Nadine Flegel, Christian Pick, and Tilo Mentler. 2021. A Gaze-Supported Mouse Interaction Design Concept for State-of-the-Art Control Rooms. In *Human Interaction, Emerging Technologies and Future Applications IV*, Tareq Ahram, Redha Taiar, and Fabienne Groff (Eds.). Springer, Cham, 208–216.

[8] Nadine Flegel, Jonas Poehler, Kristof Van Laerhoven, and Tilo Mentler. 2022. Towards Control Rooms as Human-Centered Pervasive Computing Environments. In *Sense, Feel, Design*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Marta Larusdottir, Lucio Davide Spano, José Campos, Morten Hertzum, Tilo Mentler, José Abdelnour Nocera, Lara Piccolo, Stefan Sauer, and Gerrit van der Veer (Eds.). Springer International, Cham, 329–344. https://doi.org/10.1007/978-3-030-98388-8_29

[9] Tomi Heimonen, Jaakko Hakulinen, Sumita Sharma, Markku Turunen, Lauri Lehtikunnas, and Hannu Paunonen. 2016. Multimodal Interaction in Process Control Rooms: Are We There Yet?. In *Proceedings of the 5th ACM International Symposium on Pervasive Displays* (Oulu, Finland) *(PerDis '16)*. Association for Computing Machinery, New York, NY, USA, 20–32. https://doi.org/10.1145/2914920.2915024

[10] Erik Hollnagel and David D. Woods. 2006. *Joint cognitive systems: Patterns in cognitive systems engineering*. Taylor & Francis, Boca Raton, FL.

[11] Hans-Christian Jetter, Harald Reiterer, and Florian Geyer. 2014. Blended Interaction: understanding natural human–computer interaction in post-WIMP interactive spaces. *Personal and Ubiquitous Computing* 18, 5 (2014), 1139–1158.

[12] Hanna Koskinen, Jari Laarni, and Leena Norros. 2008. Affordance table: Towards a more intuitive control room. In *Enlarged Halden Programme Group Meeting, EHPG 2008*. OECD Halden Reactor Project, OECD Halden Reactor Project, Halden, Norway.

[13] Hanna Koskinen, Jari Laarni, and Leena Norros. 2009. Activity-Driven Design Approach to the Novel Control Room Environments. In *European Conference on Cognitive Ergonomics: Designing beyond the Product — Understanding Activity and User Experience in Ubiquitous Environments* (Helsinki, Finland) *(ECCE '09)*. VTT Technical Research Centre of Finland, FI-02044 VTT, FIN, Article 25, 5 pages.

[14] Kelly Mack, John Lee, Kevin Chang, Karrie Karahalios, and Aditya Parameswaran. 2018. Characterizing Scalability Issues in Spreadsheet Software Using Online Forums. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3170427.3174359

[15] Célia Martinie, Philippe Palanque, and Marco Winckler. 2011. Structuring and Composition Mechanisms to Address Scalability Issues in Task Models. In *Human-Computer Interaction – INTERACT 2011*, Pedro Campos, Nicholas Graham, Joaquim Jorge, Nuno Nunes, Philippe Palanque, and Marco Winckler (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 589–609.

[16] Tilo Mentler, Philippe Palanque, Susanne Boll, Chris Johnson, and Kristof Van Laerhoven. 2021. Control Rooms in Safety Critical Contexts: Design, Engineering and Evaluation Issues. In *Human-Computer Interaction – INTERACT 2021*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen (Eds.). Springer International Publishing, Cham, 530–535.

[17] Tilo Mentler, Philippe Palanque, Michael D. Harrison, Kristof Van Laerhoven, and Paolo Masci. 2022. Control Rooms from a Human-Computer Interaction Perspective. In *Sense, Feel, Design*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Marta Larusdottir, Lucio Davide Spano, José Campos, Morten Hertzum, Tilo Mentler, José Abdelnour Nocera, Lara Piccolo, Stefan Sauer, and Gerrit van der Veer (Eds.). Springer International, Cham, 281–289. https://doi.org/10.1007/978-3-030-98388-8_25

[18] Tilo Mentler, Tim Rasim, Marcel Müßiggang, and Michael Herczeg. 2018. Ensuring usability of future smart energy control room systems. *Energy Informatics* 1, 1 (2018), 167–182.

[19] István Mezgár and Sonja Grabner-Kräuter. 2012. Role of privacy and trust in mobile business social networks. In *Handbook of Research on Business Social*

Networking: Organizational, Managerial, and Technological Dimensions. IGI Global, USA, 287–313.

[20] Philippe Palanque. 2021. POISE: A Framework for Designing Perfect Interactive Systems with and for Imperfect People. In *Human-Computer Interaction – INTERACT 2021*, Carmelo Ardito, Rosa Lanzilotti, Alessio Malizia, Helen Petrie, Antonio Piccinno, Giuseppe Desolda, and Kori Inkpen (Eds.). Springer International Publishing, Cham, 39–59.

[21] Rohn J. Petersen, William W. Banks, and David I. Gertman. 1982. Performance-Based Evaluation of Graphic Displays for Nuclear Power Plant Control Rooms. In *Proceedings of the 1982 Conference on Human Factors in Computing Systems* (Gaithersburg, Maryland, USA) *(CHI '82)*. Association for Computing Machinery, New York, NY, USA, 182–189. https://doi.org/10.1145/800049.801778

[22] René Reiners, Ragnhild Halvorsrud, Aslak Wegner Eide, and Daniela Pohl. 2012. An Approach to Evolutionary Design Pattern Engineering. In *Proceedings of the 19th Conference on Pattern Languages of Programs* (Tucson, Arizona) *(PLoP '12)*. The Hillside Group, USA, Article 22, 14 pages.

[23] Mahadev Satyanarayanan. 2001. Pervasive computing: Vision and challenges. *IEEE Personal communications* 8, 4 (2001), 10–17.

[24] Beth Yost, Yonca Haciahmetoglu, and Chris North. 2007. Beyond Visual Acuity: The Perceptual Scalability of Information Visualizations for Large Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 101–110.