

Abstract

In many industrial environments, especially in manual manufacturing, certain tasks still need to be performed by humans, even as automation advances. In particular, tasks such as component assembly or bonding often require an adaptability that exceeds current automation capabilities. These tasks are typically performed under time pressure, with multiple processes running in parallel at different workstations. For example, in manual production environments, multiple components must be bonded, assembled, and tested simultaneously. This complexity is compounded by the need to perform these processes quickly, accurately and in compliance with safety standards. In addition, workers must frequently move between different workstations, such as bonding, assembly, and quality control stations, further complicating the task. Success depends on the ability to quickly process complex information, make decisions, and respond flexibly to critical events.

In this dissertation, we consider an industrial use case of manual manufacturing with a focus on bonding as a representative example for the management of time-critical, parallel, and spatially distributed tasks. We propose Augmented Reality (AR) and investigate how support should be designed to reduce the complexity of these tasks. We follow the Human-Centered Design approach, in which the potential users are the starting point and benchmark for the design during development and evaluation. To this end, we analyzed the context of use through observation and expert interviews and identified key challenges such as temporal control of adhesive curing and spatial orientation of production tasks. Three research questions were derived from the analysis, which will be investigated in the dissertation: (RQ1) How can time-critical and parallel tasks be visualized within the field of view?, (RQ2) How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?, and (RQ3) How can time-critical, parallel, and spatially distributed tasks be overviewed?

Our results show that AR reduces the complexity of time-critical, parallel, and spatially distributed tasks and supports users in their execution. We show that AR instructions are preferred over traditional (paper) instructions for time-critical tasks and lead to shorter execution times. We also found that supporting parallel tasks comes with a trade-off: presenting more than two tasks reduces overall execution time, but also increases cognitive load. When time-critical and parallel tasks are also spatially distributed and users have to switch workstations to perform them, location-based AR visualizations are not sufficient and support must be provided by additional visual cues in the periphery. In this context, we have shown that existing peripheral AR cues can be encoded with temporal information. In addition, a high degree of human adaptability is required when time-critical, parallel, and spatially distributed tasks have to be taken over because the originally responsible user has to leave the workplace. For such take-over situations, we have shown that overviews with spatial registration in AR can significantly reduce cognitive load and improve task performance by integrating contextual information directly into the user's field of view.

1 Introduction

In today's industrial environments, the increasing use of automation has significantly enhanced the efficiency of many work processes. Machines and robots perform routine tasks with high precision and speed, reducing human involvement in areas such as assembly lines and quality control. However, not all tasks can be easily automated. Due to their complexity, some tasks still require a seamless interaction between people, technologies, and processes. Therefore, despite increasing automation, human skills and adaptability remain essential for tasks that require making decisions under time pressure, coordinating parallel activities, or working across spatially distributed stations [Pfe07].

For example, consider a manual manufacturing process, where workers are tasked with assembling components at different workstations. These tasks may include preparing materials, applying adhesives, ensuring proper alignment of parts, and performing quality inspections – all within strict time frames to maintain process continuity. Workers must move between stations, gather tools and materials, and adapt to changing shop floor conditions. The complexity increases when tasks are time-critical, meaning they must be completed within a specific time frame to ensure product quality. In such cases, workers are challenged to manage multiple parallel activities under time pressure, significantly increasing their cognitive load.

Examples of such time-critical industrial tasks include glass manufacturing, where workers must lubricate molds within a certain time frame to prevent production downtime, and adhesive bonding, where components must be joined within a narrow window after adhesive application to ensure proper bonding [Ras12; Hab03]. The challenge of managing time-critical tasks is not unique to manufacturing. In healthcare, for example, time-critical interventions are common in emergency rooms or intensive care units, where medical staff must respond to alarms and treat multiple patients simultaneously [Cob21]. A simple, everyday example is cooking, where timing is critical: rice can become mushy or burnt if overcooked, or undercooked if we are too impatient to wait.

Overall, three main characteristics of task complexity factors can be identified from the manufacturing process described: they are time-critical, meaning they must be completed within a specific time frame; they are often parallel, requiring workers to perform multiple tasks simultaneously; and they are spatially distributed, requiring movement between locations. Managing these tasks requires not only technical skills, but also the ability to process complex information, make quick decisions, and adapt to unforeseen changes. The responsibility here is especially high because missing deadlines or making mistakes can have significant consequences, from material loss to production delays and safety risks. In addition, the cognitive demands of these environments can be overwhelming, as workers must constantly switch between tasks, monitor their progress, and respond to unexpected problems, all within strict time constraints.

In recent years, the use of Augmented Reality (AR) has shown significant potential in assisting workers with complex tasks in industrial environments, improv-

ing the efficiency and accuracy of assembly processes [BW19; BV19; CM92]. AR systems overlay digital information onto the real-world environment to provide real-time guidance and assistance to workers. While AR has demonstrated improvements, particularly in the execution of spatially distributed assembly tasks (e.g., [RP17; HS21]), factors such as time-critical constraints [Gow+23] and parallel activities, which further increase the complexity of these tasks, have received little attention. Despite technological advances, the full potential of AR in scenarios involving both time-critical and parallel tasks has yet to be fully explored.

This dissertation addresses this gap by focusing on an industrial use case involving manual production processes, specifically adhesive bonding, to investigate how AR can be used to reduce the complexity and cognitive load of managing time-critical, parallel, and spatially distributed tasks. By integrating AR into such environments, we aim to provide workers with the tools they need to better orient themselves in time and space, ultimately improving task performance and reducing the risk of errors. Through this research, we aim to contribute to the development of more effective AR systems that address the unique challenges of managing complex tasks in modern industrial environments.

Reading Hint:

I would like to use the term „we“ instead of „I“ in this work to avoid passive constructions that are difficult to read. Nevertheless, this work was written by me as the author and contains only contributions that were planned, implemented, and executed by me.

1.1 Motivation and Goals

To introduce and better understand the topic of time-critical, parallel, and spatially distributed tasks, we would like to briefly motivate our work in this section, using the concrete and simplified use case of a cooking process.

In the following, we will describe the preparation of a recipe using Figure 1.1 and then explain the various aspects that appear in the title of this thesis.

For example, let us prepare a vegetarian moussaka with fresh salad in a very simplified way, without specifying quantities. First, slice the eggplant, potatoes, and zucchini. Then chop the onion and garlic (1, 5). Preheat the oven (3). Heat some olive oil in a frying pan and fry the potato, eggplant, and zucchini slices on both sides until lightly browned (4). Meanwhile, precook and soak the lentils (4). While the vegetables are sizzling in the pan and the lentils are precooking, you can wash the lettuce, cucumber, tomatoes, and peppers (2) and cut them into bite-sized pieces (1, 5). Remove the potato, eggplant, and zucchini slices and drain on paper towels (1, 5). In a frying pan, sauté the chopped onion and garlic and add the tomato puree (4). Add the canned tomatoes and precooked lentils to the pan, season with salt, pepper, cinnamon, and oregano and bring to the boil (4). While the tomato sauce is simmering, make the béchamel sauce (4). Gently mix the butter and flour over medium heat, then carefully stir in the milk, salt,

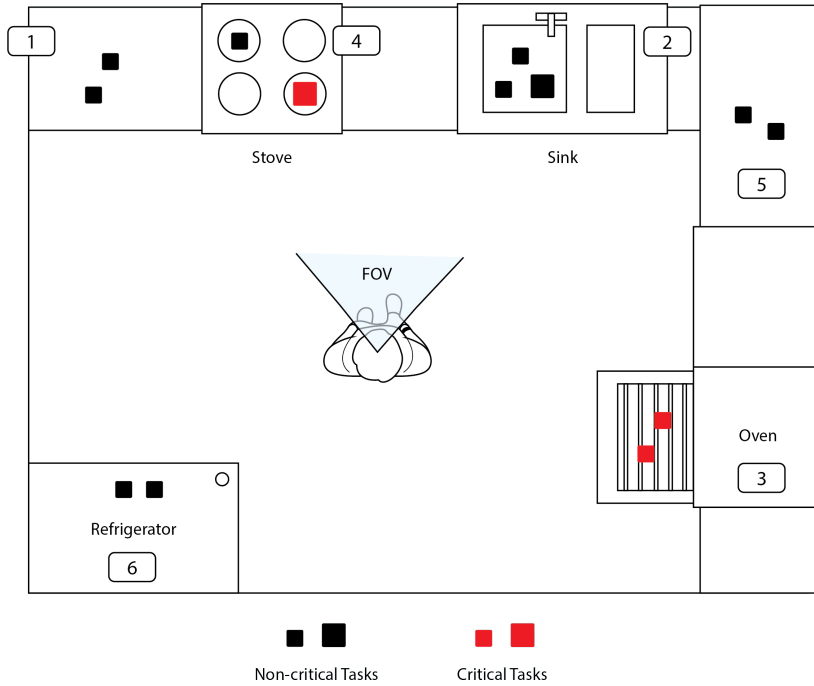


Figure 1.1: Simplified representation of a kitchen with spatially distributed tasks and different numbered workstations with a chef and his/her indicated FOV (own illustration).

pepper, and nutmeg. While the tomato and béchamel sauces are cooking, grease the baking dish (1, 5). Layer the moussaka: one layer of potato slices, one layer of eggplant, one layer of zucchini, and one layer of tomato sauce. Repeat this process until all the ingredients are used up. Finally, pour the béchamel sauce evenly over the last layer and sprinkle with grated cheese. Place the baking dish in the preheated oven and bake the moussaka (3). While the moussaka is in the oven, prepare the salad (1, 5). Place the washed lettuce leaves, cucumber, tomatoes, and peppers in a bowl. To make the dressing, mix the lemon juice, olive oil, salt, pepper, and a little balsamic vinegar in a small bowl and pour over the salad. Toss well and refrigerate until moussaka is ready (6). Meanwhile, clean the countertops and rinse the dishes in the sink. When the moussaka is done, remove it from the oven and let it rest. Then we can arrange everything and enjoy the dish.

This example is a good illustration of the different aspects of this thesis. While we can do some tasks in parallel, such as washing the salad while roasting the vegetables and pre-cooking the lentils, we can get into time-critical situations where we lose sight of the roasting and cooking tasks because we are concentrating on the task of preparing the salad. At this point, however, very few of us would be waiting in front of the stove for the cooking and frying to be done, but would instead be working on other tasks in the recipe. So we work in parallel to bridge the waiting time and finish everything at the same time if possible. The different workstations in our example (1-6) make it clear that the tasks are spa-

tially distributed and that we have to move back and forth between the different workstations to complete each task (cf. Section 2.2 and Section 3.3.2). However, the human field of view (FOV) is limited, so we cannot visually perceive tasks that are, for example, behind us. Again, tasks can become time-critical because we are simply not sensually aware of them at the moment (until we can clearly smell them). At first glance, this simple example may not seem like much of a challenge. However, when this task constellation is transferred from the private sphere to a real work process such as an industrial kitchen, multitasking, speed, and time pressure are the determining stress factors for chefs [LLH21], so that every second chef feels exhausted. For example, chefs report having to perform multiple tasks at the same time, working very quickly and often under pressure to meet deadlines and perform well. This overload can also lead to workplace accidents, such as burns from hot surfaces like the stove or oven. As described in the previous section, the responsibility for completing time-critical tasks is especially high because missing deadlines is not without negative consequences. For example, an industrial kitchen worker may have to throw out a dish, which can result in economic loss.

Our goal is to reduce the stress factors of time-critical, parallel, and spatially distributed tasks in order to enable people in different work processes to better orient themselves in time and space. In this dissertation, we gradually approach different solutions and consider different challenges to simplify working life and reduce complexity by supporting such tasks (see Section 1.3). We examine how technical support can reduce the complexity of these tasks. As indicated in the previous section, we focus on an industrial use case that is representative of other application areas in order to identify specific challenges and requirements for support. On this basis, we develop research priorities and questions that contribute to overcoming the identified challenges.

1.2 Scientific Approach

Especially when designing support options for safety-critical work scenarios, where failure to perform time-critical tasks can have negative consequences, the specific needs and requirements of users must be taken into account. Due to other factors influencing task complexity, such as spatial distribution and parallel execution of multiple tasks, the design must be such that complexity is actually reduced and people are not faced with additional challenges. To make people and their needs the starting point and benchmark for our design, we use the Human-Centered Design (HCD) process according to ISO 9241-210 [ISO11]. As a participatory process involving users [Mul02; Bod+21], it aims not only to improve technologies and systems, but also to improve people's experiences when interacting with technology.

The HCD process is designed as an iterative, abstract process and is divided into different phases (see Figure 1.2): (1) understand and specify the context of use, (2) specify the user requirements, (3) produce design solutions to meet user requirements, and (4) evaluate the designs against requirements. These phases

are iterated to incrementally improve the design [Kru14]. As we conduct basic research by investigating research questions along prototypes, we focus on the design and usability of AR support solutions following the phases of the HCD process. We consider adhesive bonding processes¹ as sub-processes of manual manufacturing and use them as representatives of other work scenarios that have to cope with time-critical, parallel, and spatially distributed tasks (see Section 3.3.3). To ensure the safety of people performing tasks in safety-critical work scenarios, we would like to refer to basic research at this point – for this reason, our results are not evaluated in the field as part of this thesis.

Parts of the work presented in this chapter were published as a paper in the journal „Neues Archiv für Niedersachsen“, in 2024 [Alt+24].

Context of Use

The context of use analysis is an important part of the HCD process to better understand the context in which users find themselves. The context is defined based on the users, the tasks, and the organizational, technical, and physical environment [ISO11]. These insights can reveal needs, problems, and limitations that the future system must address. One method in the context of use analysis is to observe users in their natural (work) environment to identify their behaviors, needs, problems, and challenges. To analyze the context of a representative use case for dealing with time-critical, parallel, and spatially distributed tasks, we conducted an observation in a real training environment of a bonding process (see Chapter 2). Our goal was to identify the work processes, tools, protective clothing, materials, and equipment used. This allowed us to observe at which steps of the bonding process potential errors and uncertainties occur on the part of the trainees. The observation was followed by interviews with experts in the field of bonding technology, who gave us a real picture of the manufacturing and assembly processes and confirmed the common sources of error that we had observed.

User Requirements

Determining user requirements and defining functional and other requirements for a system is one of the main activities in most design projects. User requirements define the specific functionalities, properties, and performance characteristics that a system must have in order to provide a suitable solution in the previously analyzed usage context [LHB10]. The context analysis resulted in several requirements for our AR support system (see Chapter 2).

Design Solutions

In this phase of the HCD process, specific design solutions are developed to meet user requirements [ISO11]. In keeping with the process, we adopt an iterative approach to incrementally improve our AR support possibilities. In this context,

¹ In the remainder of this thesis, the adhesive bonding process will be abbreviated as the bonding process for ease of reading, although both terms have the same meaning.

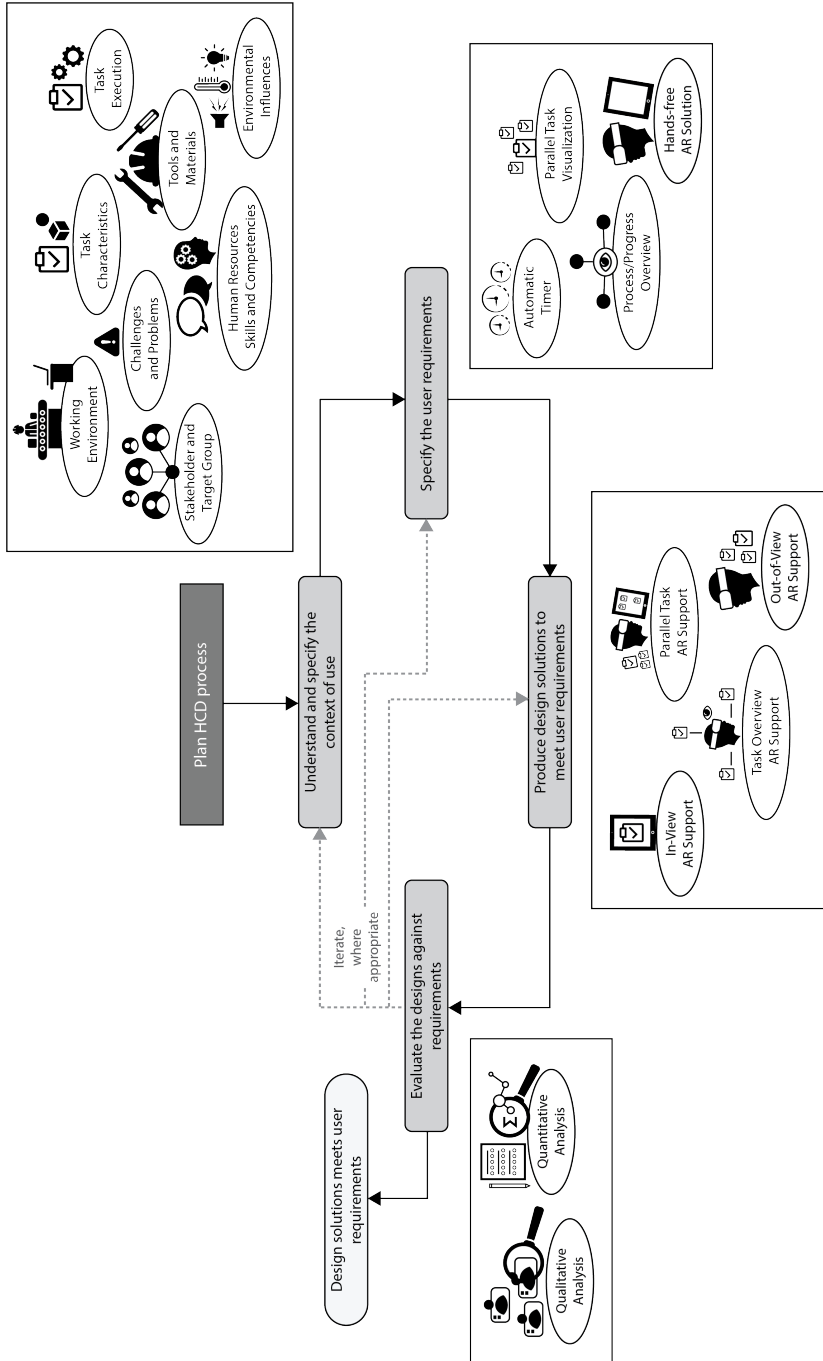


Figure 1.2: The Human-Centered Design Process (own illustration based on ISO 9241-210 [ISO11]).

design concepts improve our understanding of user needs and context, and enable us to explore and evaluate ideas and communicate design decisions [Nis15]. Design concepts can be realized through prototypes, which can vary in their level of detail and functionality. Depending on the level of detail, we can distinguish between low-fidelity and high-fidelity prototypes. The level of detail generally depends on the iteration of the process. Prototypes characterize a design before a final solution exists [Mog06]. Since the development of systems with high functionality is very time-consuming and expensive, we will not go beyond the prototype stage in this work. Our prototypes serve primarily to answer our underlying research questions, and would need to undergo further evaluation phases for use in a real working context. Each research question is addressed in a separate chapter describing the prototypes developed and the results of the study.

Evaluation

The evaluation of (interim) results is a necessary activity in the HCD process. Design and development concepts should be evaluated at an early stage to gain a better understanding of user needs. For this reason, the process includes an evaluation phase after each iteration step.

In the context of this work, the possibilities of our AR support are examined independently of the target group, which we identify in the context of use analysis and subsequent requirements specification. Since we will find out in our context of use analysis that in the real working context of small to medium-sized companies the bonding work is very often done by unskilled personnel, our non-specialized study participants are representative for the evaluation of our AR support possibilities for handling time-critical, parallel, and spatially distributed tasks. For this reason, we sought a broad age range when recruiting our study participants. This approach allowed us to explore our research questions at a fundamental level and to test whether the results could be generalized to other work contexts. Participants in our studies received no compensation and were informed that they could withdraw from the study at any time without negative consequences. All of our studies were conducted as laboratory studies, and our research has been approved by our institute's study board review.

We collected both quantitative and qualitative data for our studies.

Quantitative Data. In our user studies, we collected quantitative data using both subjective and objective measures. We used standardized questionnaires for our subjective measurements, as well as individual Likert items for specific statements that we developed. The standardized questionnaires we used include the System Usability Scale (SUS) questionnaire [Bro96] to assess usability and the NASA Raw TLX (Raw TLX) questionnaire [Har06] to measure subjective workload. The SUS was developed by John Brooke in 1996 and can be used independently of the object of investigation. The questionnaire consists of 10 statements to which participants indicate their agreement or disagreement on a scale of 1 to 5 (1=strongly disagree, 5=strongly agree). Once all statements have been answered, an overall usability score is calculated – the calculated score is between

0 and 100, with higher scores indicating better usability. The Raw TLX was developed by NASA in the 1980s and is a simplified version of the original NASA TLX that can be used to measure people's perceived workload when performing various tasks. In the simplified version, the dimensions are not weighted and participants are not required to rate the relative importance of each dimension. The overall score of the Raw TLX is therefore based solely on the direct ratings of the participants. For our individual Likert items, our participants had the opportunity to express their agreement with statements we created using 5-point Likert scales (1=strongly disagree, 5=strongly agree). The statements varied depending on the user study and research question. In our objective measures, we mainly measured task errors, time deviation, (head) movements, reaction times, precision, and process times. We report the median (Md) and interquartile range (IQR) for each of these measures. For descriptive data, such as the age of the participants, we report the mean (M) and standard deviation (SD). Our user studies have been designed as mixed, between-subjects, or within-subjects designs. In a within-subjects design, all participants participated in each condition. In a between-subjects design, each participant experienced only one condition. In a mixed design, one condition was changed between participants and another was changed within participants. All differences between groups were determined using statistical tests of variance. For the variance tests, we first determined which study design we were using. Then the type of data – ratio, interval, or ordinal – was determined. The significance level was set at < 0.05 for all tests. For our ratio or interval data, a Shapiro-Wilk test was then used to test whether the data were normally distributed. Ordinal data did not require a test for normal distribution. To test for significant differences, we needed to distinguish between between-subjects (unrelated groups) and within-subjects (related groups) when selecting the test, in addition to the normal distribution. Therefore, different statistical tests were used depending on the study design and number of groups ($=2$, >2).

Qualitative Data. In addition to collecting quantitative data, we also collected qualitative data. While quantitative data provides measurable and scalable information that lends itself well to statistical analysis, qualitative data captures the complexity of human experiences, opinions, motivations, and emotions behind the numbers. However, both the quantity and quality of the data are significantly influenced by the participants' personalities and willingness to communicate, which is why our work focuses on collecting quantitative data. To collect the qualitative data, we used the thinking-aloud protocol [BR00], where participants were asked to think aloud during the experiment to obtain qualitative feedback. The collected user feedback was then analyzed qualitatively using inductive categorization according to Mayring's qualitative content analysis [May14]. This is a structured, qualitative method for analyzing text-based data. We created categories from user statements and extracted key motifs and recurring statements. For predefined categories, such as whether a statement was positive or negative, we used the deductive approach and evaluated the participants' statements.

1.3 Thesis Outline

This thesis is divided into a total of eight chapters, the structure of which is shown in Figure 1.3. The first two chapters provide an introduction to the problem and a description of our application scenario by presenting the results of our context analysis. Chapter 3 gives an overview of the necessary background information relevant to understanding the possible contexts of this thesis. Chapter 4 then presents our conceptual design decisions developed to address our research questions. Chapters 5 to 7 present the related work and the user studies conducted to answer the derived research questions. The final chapter reflects on our findings and identifies potential avenues for future research.

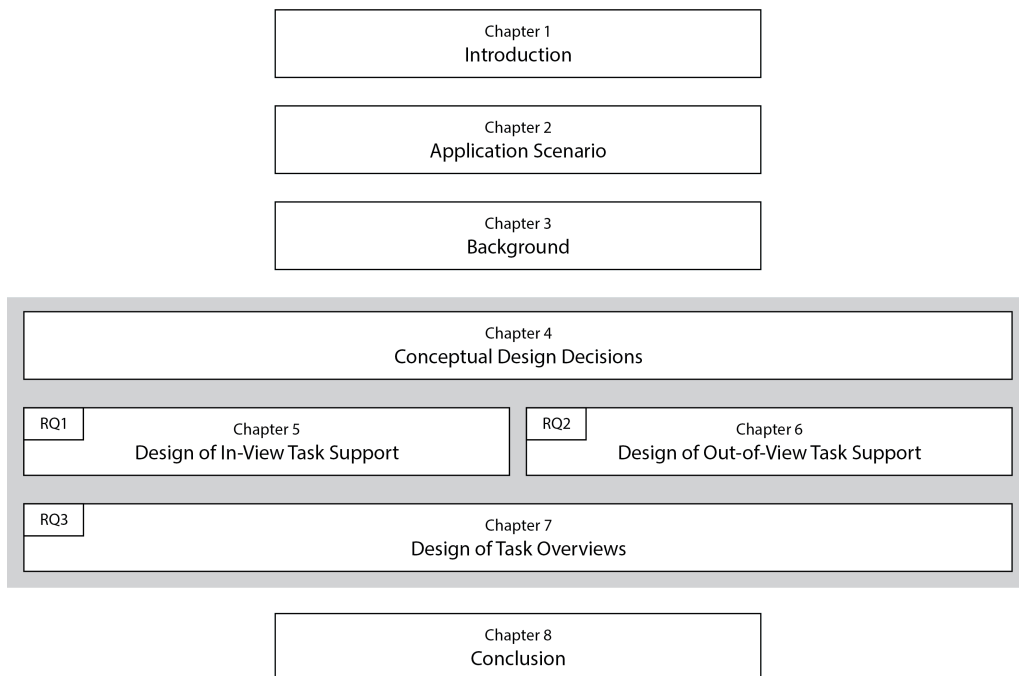


Figure 1.3: Outline of the thesis. Chapters 1 and 2 cover the introduction as well as the application scenario of the thesis. Chapter 3 presents the background of the thesis. Chapter 4 describes the conceptual design decisions that were developed. Chapters 5 to 7 present the user studies conducted to answer research questions RQ1 - RQ3. Chapter 8 provides a discussion of the results and contributions and highlights potential directions for future work (own illustration).

The chapters of this thesis are described in more detail below.

Chapter 2: Application Scenario

In the second chapter, we identify the specific challenges that need to be addressed in the context of this work. First, we present the results of our observation of an industrial use case as part of the context analysis of the HCD process. We then describe the subsequent expert interviews and explain the derived requirements for supporting time-critical, parallel, and spatially distributed tasks. Finally,