Master thesis

Development of a Pick-by-Light Assistance System in a Sheltered Workshop: A User-Centred Approach

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Kurzfassung

Moderne Fertigungsumgebungen sollen zunehmend Effizienz mit sozialer Inklusion in Einklang bringen, insbesondere da sie vielfältige Arbeitskräfte integrieren, zu denen auch Menschen mit Behinderungen gehören. Traditionelle, papierbasierte Methoden, obwohl sie seit Langem etabliert sind, führen häufig zu kognitiver Überlastung, Kommunikationsbarrieren und betrieblichen Ineffizienzen. Angesichts sich wandelnder EU-Richtlinien und eines verstärkten Fokus auf gerechte Beschäftigungschancen besteht ein dringender Bedarf, innovative Assistenztechnologien einzuführen, die sowohl die Produktivität als auch das Benutzererlebnis in inklusiven Produktionsumgebungen verbessern.

Diese Arbeit stellt die Entwicklung eines Pick-by-Light-Assistenzsystems vor, das speziell für eine Werkstatt für Menschen mit Behinderungen konzipiert wurde. Unter Anwendung eines benutzerzentrierten Designansatzes kombiniert die Studie fortschrittliche digitale Schnittstellen mit inklusiven Gestaltungsprinzipien, um ein System zu entwickeln, das Arbeiter bei komplexen Montageaufgaben unterstützt. Der Entwicklungsprozess wird von der anfänglichen Anforderungsanalyse und iterativen Prototypentwicklung bis hin zu umfassenden Evaluationen detailliert beschrieben, wobei Verbesserungen in Bezug auf Benutzerfreundlichkeit, Zugänglichkeit, Bedienungsleichtigkeit und allgemeine Zufriedenheit im Vergleich zu herkömmlichen Methoden hervorgehoben werden.

Umfassende Benutzerbewertungen zeigen, dass das Pick-by-Light-System konventionelle, papierbasierte Ansätze deutlich übertrifft, indem es eine verbesserte Aufgabenleistung, mehr Komfort und eine insgesamt höhere Benutzerzufriedenheit erzielt. Diese Ergebnisse bestätigen nicht nur das Design und die Implementierung des Systems, sondern liefern auch wertvolle Erkenntnisse zur Integration von Technologie in inklusiven Fertigungsumgebungen. Die gewonnenen Erkenntnisse tragen zur Entwicklung effizienterer und gerechterer Produktionsprozesse bei und ebnen den Weg für zukünftige Innovationen im Bereich des Assistenzsystemdesigns.

Schlüsselwörter: Assistenzsysteme, User Centric Design, Accessibility, Human-Machine-Interaction, Sheltered Workshop WfbM.

Abstract

Modern manufacturing environments are increasingly expected to balance efficiency with social inclusion, particularly as they integrate diverse workforces that include individuals with disabilities. Traditional paper-based methods, while long-standing, often lead to cognitive overload, communication barriers, and operational inefficiencies. With evolving EU policies and a growing focus on equitable work opportunities, there is a pressing need to adopt innovative, assistive technologies that enhance both productivity and user experience in inclusive production settings.

This thesis presents the development of a Pick-by-Light assistance system tailored for a sheltered workshop environment. Utilizing a user-centered design approach, the study combines advanced digital interfaces with inclusive design principles to create a system that supports workers in complex assembly tasks. The work details the process from initial requirements analysis and iterative prototyping to comprehensive evaluations, emphasizing improvements in usability, accessibility, ease of use, and overall satisfaction compared to traditional methods.

Comprehensive user evaluations indicate that the Pick-by-Light system significantly outperforms conventional paper-based approaches, demonstrating enhanced task efficiency, comfort, and overall user satisfaction. These results not only validate the system's design and implementation but also provide valuable insights into the broader challenge of integrating technology in inclusive manufacturing environments. The findings contribute to the development of more efficient and equitable production processes, setting the stage for future innovations in assistive system design.

Keywords: Assistive Systems, User-Centered Design, Accessibility, Human-Machine Interaction, Sheltered Workshop.

Contents

Chapter 1
Introduction

1.1 Motivation and Problem Statement

Modern industrial advancements are increasingly emphasizing the integration of digitalization with human creativity to create efficient, flexible, and user-centered manufacturing environments. Additionally increasing demand for mass customization, particularly in one-off production environments where product designs frequently change [1]. The main drawback of current manufacturing practices is that they are often reliant on paper-based instructions, and present limitations such as cognitive overload, communication barriers, and inefficiencies [2]. Studies indicate that errors frequently arise due to excessive or irrelevant information, as well as distractions caused by traditional instruction methods [3]. It is highly necessary to maintain manufacturing flexibility and ensuring high-quality output requires skilled workers and clear instructions [4]. In light of these operational challenges, it is essential to recognize that technological improvements must also address the human element in production.

While these concerns remain relevant, it is also increasingly becoming relevant to keep inclusivity of workers and provide equal working opportunities to people of varying capabilities and needs. EU policies, including the Council Directive 2000/78/EU, underscore the importance of equal employment opportunities by mandating accessible work environments for individuals with disabilities. In fact, EUROSTAT provides statistical data for the European Union (EU) area, showing that only 38.7% of individuals with disabilities aged between 25 and 65 are employed [5]. Therefore, in this transformative landscape, the European Commission (European Council (EC)) plays a pivotal role by advocating for industrial models that balance economic growth with social well-being and inclusivity [6]. Individuals with disabilities, including hearing, visual, cognitive, or physical impairments, often encounter significant challenges in manufacturing environments due to the complexity of instructions and communication barriers. These obstacles can hinder their effective integration into production areas.

As these trends in industrial setups evolve, there is a growing focus on human-machine interaction that harnesses advanced technologies to foster sustainable and resilient production systems [7] that also consider better working environments and worker satisfaction. This trend is not only transforming operational processes but also reshaping the very nature of work in industrial settings. This shift in focus has paved the way for integrated solutions that address both productivity and inclusivity.

This necessitates the use of assistive systems; these systems are integrated technological solutions designed to support human operators in performing tasks more efficiently with greater worker satisfaction. These assistive technologies not only enhance job performance but also increase employment rates among people with disabilities by addressing accessibility challenges and promoting independence [8]. These serve as a one-stop solution to address these challenges, integrating the benefits of both digitalization and human creativity while enhancing worker performance, well-being, user experience, and overall industrial workflow efficiency [3]. Moreover, the success of these systems depends on ensuring that they are designed for all users.

Additionally, inclusive design principles ensure that these systems cater to the diverse needs of all workers, fostering an environment where individuals with disabilities can thrive alongside their peers. Inclusive design focuses on creating products, services, and environments that are accessible and usable by as many people as possible, regardless of their abilities or backgrounds. It involves engaging diverse users throughout the design process to ensure that solutions are flexible, adaptable, and barrier-free. This user-centered approach not only enhances usability and efficiency but also promotes social inclusion and equity. By integrating such systems, manufacturing industries can move towards more inclusive and efficient production processes [9]. Bridging the gap between technological innovation and social inclusion is crucial for modern manufacturing.

These challenges, which contribute to frequent errors and disproportionately affect workers with disabilities who face difficulties with complex, non-adaptable systems, underscore a critical gap in existing manufacturing processes. Consequently, there is an urgent need for the development and implementation of integrated assistive systems with inclusive design principles with intuitive user interfaces that not only streamline production workflows and enhance job performance but also promote equitable employment opportunities and social inclusivity.

For example, at Wien Work, a company established under the Disabled Persons Employment Act and the Vienna Equal Opportunities Act, over 70% of employees have some form of disability. Workers reported difficulties managing multiple paper-based instructions, that must be kept organized and followed sequentially to complete even simple tasks, which leads to increased errors and user frustration. Among these, the workers with hearing impairment faced a high level of communication barriers. Assistance systems with accessibility, user-centric considerations such as the ones discussed above could act as solutions to address inclusivity, user satisfaction, and experience while also staying relevant by increasing efficiency and worker performance in these situations.

1.2 Outcomes

This study aims to explore feasible technological solutions that enhance user experience in industrial work environments while addressing key qualitative factors such as usability, accessibility, ease of use, comfort, overall satisfaction, and perceived efficiency. Assistive systems hold great potential for improving workplace inclusivity, particularly for workers with disabilities, by providing structured guidance and interactive support.

A major shortcoming of current solutions is the lack of a unified approach that integrates assistive technologies, interactive user interfaces, accessibility guidelines, and User-Centric Design (UCD) principles. Assistive technologies offer both digital and physical support to help workers perform tasks more efficiently, while UCD ensures that these solutions cater to diverse user needs by creating tailored support systems for different abilities and experience levels [10]. A well-structured User Interface (UI) serves as the bridge between humans and assistive systems, enabling clear and intuitive interactions. This study seeks to address this gap by examining how a holistic integration of these elements can lead to more practical and effective solutions.

By incorporating cognitive assistance technologies along with structured guidance, clear visual cues, and real-time feedback mechanisms, this research aims to enhance user engagement and mitigate task-related challenges, particularly for workers with disabilities [6]. These features can help users navigate complex tasks more effectively, reduce errors, and improve the overall user experience [7]. Prior research [11] has already demonstrated success in improving task efficiency in dynamic industrial settings, underscoring the potential of these solutions.

To validate the effectiveness of these technologies, this study employs an iterative development methodology incorporating usability testing, user feedback, and performance evaluations [12]. By bridging the gap between traditional and modern industrial workflows, this research aims to foster a more inclusive and efficient production environment. Furthermore, it seeks to develop solutions that are not only conceptually sound but also practical and application-ready for real-world implementation.

1.2.1 Research Questions

Based on the identified research gap, this study formulates key research questions aimed at addressing the challenges and opportunities in achieving the above-mentioned outcomes. These questions serve as a foundation for guiding the investigation and evaluating the effectiveness of proposed solutions.

- What are the challenges in integrating assistive technologies in manufacturing, and how can stakeholder involvement address these challenges?
- What factors and strategies should be incorporated into user interface design to create an intuitive and effective interaction experience for workers with varying cognitive and physical needs?

- Which system and considerations could support assembly workers at Wien Work and how do they perceive the developed solution in the context of usability and usefulness?

1.3 Methods

To address the research questions, this study employed a structured methodology integrating a systematic literature review, iterative prototyping, and user evaluations. The methodology consisted of three key phases: a systematic literature review to establish theoretical foundations, the development of a prototype assistive system, and evaluations to assess the effectiveness of the proposed solution.

1.3.1 Literature Review

A literature review was conducted to synthesize existing research on assistive technologies, UCD, and user experience evaluation. The search was performed using databases such as IEEE Xplore, ACM Digital Library, Scopus, and Google Scholar. Keywords including *"assistive technology in industry," "user experience in industrial environments," and "UCD for accessibility,"* guided the selection of relevant studies. Inclusion criteria focused on peer-reviewed journal articles, conference proceedings, and books published within the last ten years, ensuring recency and empirical validation.

The literature review covered three main areas. First, it examined the challenges faced in industrial work environments and how assistive technologies improved efficiency and enhanced worker satisfaction [13]. Second, the review explored UCD principles to ensure assistive systems remained intuitive and accessible. Third, studies on user satisfaction, usability, accessibility, acceptance, and system effectiveness were analyzed to understand the impact of assistive technologies on workplace experience [14]. Well-designed assistive systems were anticipated to improve job satisfaction and foster confidence among workers. Evaluation methodologies such as structured interviews, focus groups, and user satisfaction surveys were examined to provide insights into how different user groups interacted with these systems.

Furthermore, the literature review investigated strategies for effective stakeholder involvement in the development of assistive technologies. Research suggested that engaging end-users, managers, and accessibility experts throughout the design process fostered better alignment between system functionalities and real-world needs. Ensuring that the assistive technology reflected diverse perspectives could enhance adoption rates and long-term usability. Additionally, the review explored creativity-driven approaches in assistive system design, identifying methods that supported iterative experimentation, user-driven modifications, and the integration of innovative interaction models.

The findings from the literature review informed the design and development of the assistive technology prototype, ensuring that it was grounded in established principles of usability, accessibility, and user experience.

1.3.2 Prototype Development

The study employed an iterative prototyping approach to ensure that the developed assistive system was both functional and user-centric. The design process began with conceptual wireframing based on insights from the literature review. Low-fidelity prototypes were initially developed to validate UI layout, interaction flow, and accessibility features before progressing to high-fidelity implementations.

Through multiple iterations, the prototype underwent refinement based on real-world user feedback, addressing usability concerns and enhancing system efficiency. The iterative nature of prototyping allowed for continuous testing and validation, ensuring that the interface effectively met user needs [15]. By involving stakeholders throughout the process, valuable insights were incorporated, fostering user acceptance and facilitating integration into industrial workflows.

Furthermore, prototyping was expected to enhance creativity and support user-centered development by allowing experimentation with different UI elements and interaction models. Adaptive features were explored to accommodate different user preferences and disabilities, ultimately optimizing the overall user experience. The prototype also served as a tangible artifact that facilitated communication between researchers, developers, and end-users, promoting better collaboration and shared understanding.

A more detailed discussion of the prototyping approach, including types of prototypes, testing methodologies, and evaluation criteria, was presented in Section 4.4.

1.3.3 Evaluation Methodology

The evaluation phase employed a qualitative, user-centered approach to assess the assistive system's usability, accessibility, and overall effectiveness. The methodology integrated user testing, focus groups, and structured interviews to gather comprehensive feedback.

User testing involved direct interaction between participants and the developed system, allowing researchers to document experiences, identify usability challenges, and refine design aspects. Participants, including individuals with disabilities, were recruited to ensure inclusivity in evaluating the system's accessibility and effectiveness.

Structured interviews and post-interaction surveys were conducted to capture user perceptions of the system's intuitiveness and satisfaction levels. Participants provided qualitative feedback through semi-structured discussions, while questionnaires quantified responses related to ease of use, efficiency, and overall user experience.

Additionally, focus group discussions were incorporated to gain deeper insights into how different user demographics interacted with the assistive system. These discussions allowed researchers to explore user expectations, usability pain points, and suggestions for improvement in a collaborative setting. Focus groups helped identify patterns in user experience that might not have emerged through individual testing sessions. These procedures ensured that the assistive technology aligned with real-world industrial requirements and effectively enhanced workplace inclusivity.

This study adopted a structured methodology that integrated a systematic literature review, iterative prototyping, and user evaluation. The literature review established theoretical foundations and best practices, the prototyping phase translated these insights into a functional assistive system, and the evaluation phase validated the system's effectiveness in real-world conditions. By combining theoretical and empirical approaches, the study aimed to develop an accessible and user-centered assistive technology that enhanced industrial work environments.

1.4 Structure of the Work

The thesis work is organized in a structured format to address all the above research questions and the above-described assumptions are examined in detail in this work and also contribute to building a successful instructive assistant system to improve user experience. The following points outline the summary of the key areas covered in each chapter of the thesis work. This structured approach ensures a logical progression, linking theoretical insights to practical applications, ultimately guiding the development of an effective instructive assistive system for industrial settings.

- **1 Introduction:** This chapter provides an overview of the research, including a detailed problem statement that outlines the challenges and motivations behind the study. It also presents the expected outcomes of the research and the methodological approach adopted to address the research questions.

- **2 Theoretical Foundation:** This chapter explores the fundamental concepts underpinning assistive systems, including their significance in industrial settings. It also discusses key aspects such as UI design, accessibility considerations, and user-centric design principles to establish a strong theoretical basis for the research.

- **3 Literature Review:** This section analyzes current technological advancements in the field of assistive systems and identifies research gaps that need to be addressed. It presents an overview of relevant studies and highlights the need for new approaches to improve user experience, efficiency, and accessibility in industrial environments.

- **4 Methodology:** This chapter details the research design, outlining the processes involved in prototype development, data collection, and evaluation methods. It explains how iterative prototyping and qualitative assessments were used to validate the assistive system, ensuring that it meets user needs effectively.

- **5 Evaluation:** This section presents the findings from prototype testing and user feedback. It includes a discussion on usability, accessibility, and system effectiveness, derived from user testing, focus group discussions, and survey responses.

- **6 Discussion:** This chapter interprets the evaluation results in relation to the research questions and existing literature. It highlights key insights, discusses implications for industrial applications, and identifies areas for improvement. Additionally, it provides recommendations for refining the assistive system and making it more adaptable for diverse users.

- **7 Conclusion:** The final chapter summarizes the key findings and contributions of the study. It reflects on the research outcomes, their significance, and potential future directions for further development and innovation in the field of assistive systems.

Chapter 2

Theoretical Foundation

2.1 Assistive Systems in Manufacturing

The technological and computational developments in recent years have led to rapid changes in production processes and also human roles in production. Industries are getting more digitalized, improving connectivity between different machines, and the concept of smart and connected factories using Internet of Things (IoT). This has helped the collection of big data for analyzing the process data to find hidden patterns, enabling them to pursue continuous improvement and optimizing the processes by constantly controlling and monitoring production using digital devices. These data are difficult to analyze for a human operator in real time. One additional challenge in modern industrial setups is to enhance inclusivity and diversity and the goal is to enhance and support the existing physical capabilities of workers to overcome human physical limitations, as well as to assist operators with special needs. These challenges can be addressed by using adaptive and flexible assistive systems, which are increasingly needed to meet the growing demands for customization. These systems support manual workers by guiding them through the manufacturing process and enhancing human capabilities and are referred to as assistive systems in manufacturing. Assistive systems include systems in manufacturing to help operators in terms of monitoring and controlling manufacturing processes, provide an overview and additional information on products and materials, help understand complex interactions between machines and processes, assist in overcoming abnormal situations, ergonomic challenges, process available data and information to the operators. This leads to the classification of assistive systems into three main categories: (1) sensorial, (2) cognitive, and (3) physical worker assistive systems [16] as represented in the figure below.

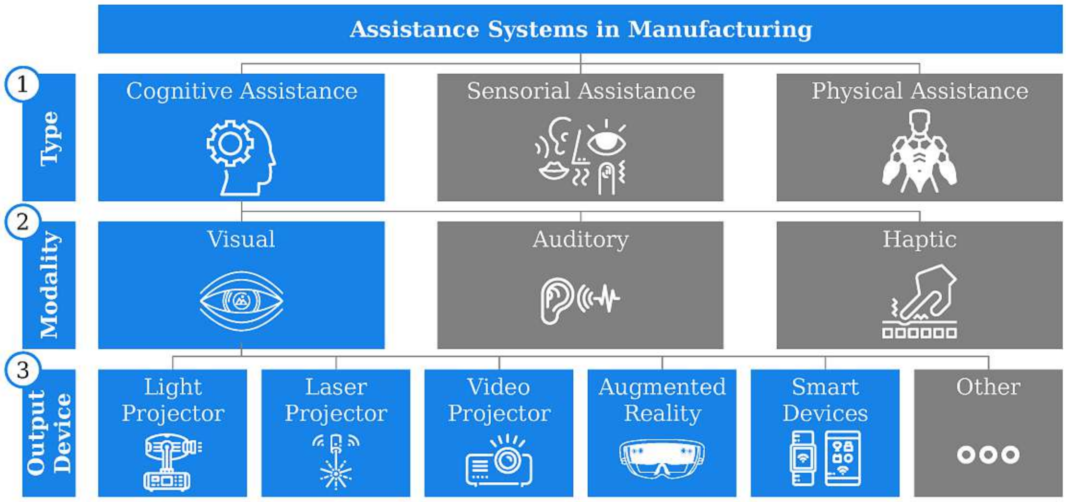


Figure 2.1.: Classification of Assistive Systems in Manufacturing [17]

Assistive systems have been used in various manufacturing processes, including assembly, dismantling, information management, training, and inspections. In assembly lines, these systems have proven effective in providing human operators with real-time information from the broader manufacturing line while they perform assembly tasks [18]. Identifies various applications of assistive systems in manufacturing.

Sensorial assistive systems focus on enhancing human sensory perception by providing real-time visual, auditory, or haptic feedback. These systems improve interaction with machinery and processes by ensuring that operators receive critical alerts, guiding workers with precise instructions, and compensating for sensory impairments.

Cognitive assistive systems help workers process and interpret complex information by analyzing data, providing decision-support, and optimizing workflows. In industrial environments, cognitive assistance can take the form of intelligent dashboards, adaptive work instructions, and automated alerts that help workers focus on critical tasks rather than processing large amounts of raw data. These systems reduce cognitive overload, enabling operators to respond more efficiently to changing conditions.

A physical assistive system refers to a device designed to support, enable, enhance, or assist physical movements—whether stationary or in motion—by mechanically interacting with the user's body or directly handling the workpiece. These include physical assistive systems, such as exoskeletons and robotic systems, which assist workers physically to improve ergonomic conditions and enhance employee satisfaction in various occupational tasks, in which examples include tasks like overhead work, using tools, moving around, squatting, and carrying loads [19]. Some applications may be like the ones below:

- **Assembly and Dismantling:** Factory operators use light-based indicators to identify the correct containers to pick from unique part bins, a system known as 'pick-by-light'. Incorporating the use of sensory data from machinery and equipment allows for real-time visualization of assembly line information on computers. Additionally, workflow structure and efficiency can be enhanced in the early design stages by implementing an AR environment in pilot production lines.

- **Information Management:** Assistant systems help workers receive just-in-time data from built-in sensors by supporting data visualization for the work being performed. Assistive systems also enable workers to avoid reading physical manuals and guidelines while performing tasks, as this information can be stored in a database and strategically presented in the worker's field of view.

- **Training and inspection:** They can also be applied in the training process of users in industrial environments, helping to boost productivity and improve training effectiveness. Additionally, they contribute to quality assurance in manufacturing lines through the use of spatial augmented reality technology.

2.2 Historical and Contemporary Overview of Assistive Technologies in Disabilities

Historically, assistive technologies have been in use for centuries. Early innovations—such as eyeglasses developed in Italy during the 13^{th} century and wheelchairs emerging from 5^{th} century China—exemplify devices that can be classified as assistive systems. The term 'Assistive Systems' refers to equipment or products that are designed, modified, or customized to improve, maintain, or enhance the functional abilities of users [20]. Official recognition of these systems began with the Technology-Related Assistance for Individuals with Disabilities Act of 1988, and as outlined in the International Standard Organisation (ISO) standard 9999:2016, assistive systems encompass a wide range of technologies including devices, tools, instruments, and software intended for use by people with disabilities.

In contemporary settings, assistive systems serve as valuable tools to enhance inclusivity and improve the performance of individuals with special needs or disabilities. However, their successful implementation has encountered numerous challenges. Factors such as accessibility, product cost, design limitations, usage levels, government policies and regulations, user awareness, and knowledge limitations contribute to these challenges. For example, the Law on Disabled Persons 2014 emphasizes accessibility by ensuring the equitable distribution of resources so that everyone has equal opportunities to access tailored products and services [21]. A significant barrier is the lack of awareness regarding available assistive systems and access to the necessary services and products. Health centers, along with government and non-governmental organizations, are therefore recommended to develop skills and awareness initiatives to guide individuals with disabilities toward appropriate technologies, as noted in the World Intellectual Property Organisation (WIPO) Technology Trends 2021: Assistive Technology report [22].

Another major challenge is achieving effective adaptability in assistive systems, which refers to their ability to adjust dynamically to the diverse needs of users and to operate efficiently under varying environmental conditions. To overcome this, designers must focus on creating intuitive, user-friendly systems while actively bridging the knowledge gap between users and developers through continuous knowledge exchange and the application of UCD principles. Röcker [?] proposed an approach emphasizing these strategies. Additionally, factors such as practical usefulness, ease of maintenance, environmental compatibility, user language preferences, visual resolution and display settings, the appropriate level of detail in information, interface customization, context awareness, accessibility features, and cognitive load management are critical to enhancing the overall adaptability of assistive systems.

The World Health Organisation (WHO) (2022) has also outlined considerations to strengthen assistive systems by addressing policy, product, provision, and personnel elements. Policies should support funding and initiatives that ensure universal access by integrating assistive systems into health and social frameworks. In terms of product design, a focus on usability, accessibility, and user-centered design is essential. Provisions must include training, accessible information, and regular product updates, while personnel support remains a key element in ensuring effective service delivery.

Additional studies, such as those by Addis et al. [23] and Steel et al. [24], highlight similar challenges in regions like Africa, where financial constraints, limited access to devices and maintenance services, policy implementation gaps, and societal unawareness further complicate the integration of assistive systems. These multifaceted challenges call for a comprehensive approach that considers both technological and social dimensions to fully empower users and enhance the efficacy of assistive technologies.

2.3 Instruction Provision Systems

Industrial environments have traditionally relied on paper-based instructions, which often fail to meet the diverse needs of today's workforce. Such static formats can increase cognitive load and exclude workers with disabilities by lacking accessibility. In contrast, digital instructional assistance systems offer flexible, multimodal communication that can be tailored to individual needs, reducing errors and enhancing inclusivity. Embracing these systems is essential for creating an efficient and accessible production environment.

Instructional assistant systems are a type of assistive technology designed to provide guidance, instructions, and support to users, often in real-time, to help them perform tasks, learn new skills, or navigate environments more effectively. These systems offer significant advantages in assembly tasks and enhance the quality of outcomes by integrating various technologies like displays, projectors, light-assisted systems, mixed reality, and virtual reality with user interfaces. For instance, MR interfaces, like smart glasses, enable workers to receive essential assembly information quickly, reliably, and interactively. Unlike traditional Augmented Reality (AR) applications, Mixed Reality (MR) not only overlays virtual objects but also anchors them to the physical environment, showing instructions directly on the item being assembled.

Building on this concept, workers can utilize Head Mounted Displays (HMD) devices to view 3D models and animated, step-by-step instructions directly within their line of sight, providing valuable assistance for assembly and maintenance tasks. Compared to traditional manuals, this solution provides a fully hands-free experience while offering contextual tools and information necessary to perform tasks efficiently. MR also enhances situational awareness, which is critical in dynamic environments. However, these extended reality solutions may have drawbacks in industrial settings, as they can reduce or eliminate environmental awareness, posing safety risks in environments where awareness is crucial.

In contrast, systems like pick-by-light, as demonstrated by Stockinger et. al. [25], offers notable benefits in terms of situational awareness, reduced user strain, enhanced task performance, and an accessible, engaging work experience. These systems provide immediate visual cues—such as highlighting the exact items or locations to be picked—without obstructing the user's field of view, which is a distinct advantage over head-mounted displays that can impair peripheral vision and cause discomfort. However, the information delivered by pick-by-light is inherently limited to basic directional guidance and simple alerts.

To address more complex tasks, it is beneficial to pair pick-by-light with supplementary interfaces. For example, user interfaces that can complement pick-by-light by providing detailed task instructions, and real-time updates [26] have been proposed. This integrated approach not only enriches the information available to the operator but also supports better decision-making in production environments. Moreover, such hybrid solutions are particularly advantageous for workers with disabilities, as they combine the low cognitive load and unobtrusive nature of pick-by-light with the comprehensive, customizable support offered by UI systems [27].

When compared to traditional paper-based instructions—which are static, difficult to update, and often unsuitable for individuals with diverse accessibility needs—this multimodal approach enhances both safety and efficiency in industrial settings.

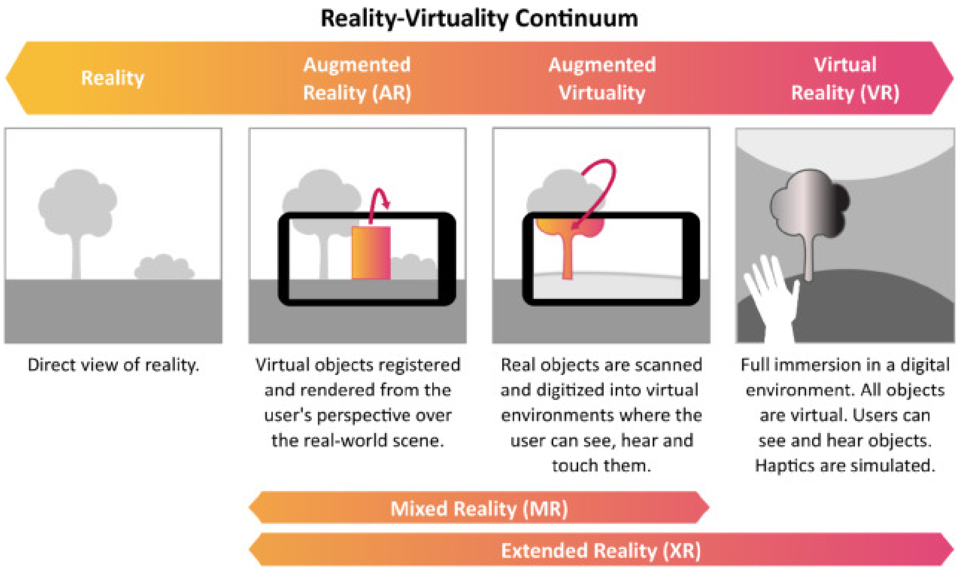


Figure 2.2.: Variations of Extended Realities [28]

2.4 User Interface Design

The advancement of new-age technologies such as Cloud Manufacturing, IoT, cyber-physical systems, and Data analysis is driving the evolution of 'smart factories'. These factories are capable of making intelligent decisions and managing their manufacturing processes by leveraging complex, high-volume, high-velocity data, which demands significant computational power for compilation, analysis, and deriving insights, as previously discussed. Effective data visualization in industrial settings offers several benefits, including enhanced decision-making, better ad hoc analysis, and improved collaboration, all of which contribute to the industry's transformation. These benefits are supported by intuitive visualization user interfaces that simplify the analysis and understanding of data, enabling the workforce to provide valuable insights for optimizing manufacturing processes [29]. Leveraging natural visual abilities is inherently intuitive, requiring little to no training or expertise in managing data. A web-based user interface with high user engagement and accessibility would improve ease of use and ensure broader access for individuals with varying abilities, including people with disabilities, elderly individuals, and those with minimal training, compared to traditional Human Machine Interaction (HMI) counterparts. Many modern web-based development frameworks offer customizable interfaces and demonstrate potential in managing big data.

In its early stages, the focus of Human-computer Interaction (HCI) was primarily on efficiency, usability, and functionality, often overlooking the role of aesthetics and interface formats in shaping users' experiences and emotions. Cheng Hsu [30] highlights the design principles and critical factors that influence different styles of web-based visual user interfaces. The study identifies two crucial categories of factors that significantly impact user satisfaction and evaluation: 'emotional factors' and 'functional factors'.

Functional factors consist of six design criteria: usability, hyperlinks, structure, ease in the display of information, title or logo design, and text readability. Emotional factors, on the other hand, include five design criteria: attractiveness, color schemes, willingness to read, image promotion, and layout design. These factors are pivotal in creating interfaces that are both interactive and intuitive.

Although websites may vary in subject matter, their visual interface styles often appear similar due to shared purposes, production technologies, bandwidth limitations, or functional requirements. Based on these influences, the study identifies six broad types of web visualization styles: frames and color blocks type, text-first type, rational layout type, image-centered type, emotional and curvy type, and cartoon-like type. These styles are shaped by the aforementioned factors, and users prioritize these factors based on their preferences, aiding in the selection of a suitable website style [30].

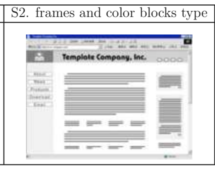
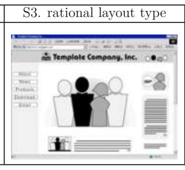
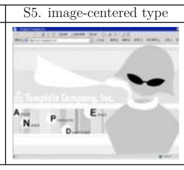
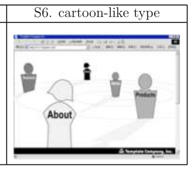
S1. text-first type	S2. frames and color blocks type	S3. rational layout type	S4. emotional and curvy-centered type	S5. image-centered type	S6. cartoon-like type
					

Table 2.1.: six typical webpage styles [30]

In addition to these factors, the intuitiveness of the interface plays a vital role in enhancing the user experience in interface design. Intuition is a type of cognitive processing that operates largely unconsciously, drawing on accumulated experiential knowledge. This process harnesses familiar emotional factors, as previously discussed, to facilitate swift and seamless user engagement with the interface during the initial encounter.

The first step in understanding design parameters is identifying users and their needs. This includes defining the target audience for the interface and collecting information about users' familiarity with similar systems. This foundational step ensures the design aligns with user expectations and improves usability. To assess the familiarity of different emotional and functional factors, designers could make use of questionnaires such as Technology Familiarity Questionnaire (TFQ) to determine the priority levels of these parameters to the users.

Blacker and Popovic [31] also explored the relationship between well-known aging factors, such as reaction times and cognitive processing, during interactions with interfaces. They proposed three principles to guide designers in creating interfaces for intuitive use. These principles can be applied to both redesigning and evaluating the intuitiveness of interfaces:

- **Principle 1:** Utilize familiar symbols and terms for common functions, place them in expected or familiar positions, and ensure the functions resemble similar ones that users have previously encountered.

- **Principle 2:** Use metaphors to make unfamiliar concepts relatable by connecting them to existing, well-known ideas.

- **Principle 3:** Maintain uniformity in the function, placement, and visual representation of features throughout the design and within each section.

Hui et. al. [32] proposed a customized UI to enhance user experience. In accordance with the Technology Acceptance Model (TAM), perceived ease of use and perceived usefulness are critical for improving user experience. Interfaces designed to facilitate the needs of general users often fail to address the specific requirements of individual users. A custom-built UI would better serve such needs by directly catering to them.

However, using multiple services simultaneously can increase the effort required to learn and navigate each platform. A single cloud service may be insufficient, while relying on multiple services can become cumbersome, reducing the perceived ease of use and, consequently, the likelihood of accepting web applications. Additionally, the study emphasized that clarity and a sense of control are essential factors for improving system acceptance among target users.

To meet the requirements outlined above, a successful modern web application should be built on an efficient web development framework, as this is one of the most critical factors for achieving functionality, scalability, and a seamless user experience. An effective framework can streamline development, support modular design, and provide essential tools and libraries that facilitate the integration of features like intuitive UI, real-time interactivity, and responsive design.

2.5 User-Centered Design

When developing assistive systems, it is crucial to consider various factors to ensure optimal user satisfaction, experience, usability, and performance. These goals are best achieved by applying human factors engineering principles throughout the design process. A fundamental requirement in the design of assistive systems is the involvement of end-users and a diverse group of participants from the outset, as emphasized by Röcker [33]. This approach ensures that the system meets the needs of a broad audience, fostering future inclusivity. Röcker highlights the need for user integration, noting that while system designers and engineers possess deep technical expertise, they often lack insight into the social context of the application. This gap can lead to inaccessibility for large sections of the population, including age sensitivity, disability inclusion, and cultural considerations. Early adoption of UCD can also result in significant financial benefits, as the cost of adapting technical concepts and service functionalities is considerably lower when changes are made in the early stages of design.

The International Organization for Standardization supports user-centric design through guidelines such as ISO 6385 for system design and ISO 9241-210 for interactive systems. These standards emphasize the importance of human-centered design considerations throughout the entire product lifecycle, which is divided into five phases: define, imagine, support, realize, and retire [7]. The design of assistive systems must address several key challenges, including accommodation problems, navigation performance, display unit resolution, and ergonomic considerations.

A user-centered design approach is essential for creating usable and effective visualization solutions. UCD involves active user participation throughout the development process to meet specific user needs. Key principles of UCD include a thorough understanding of user goals, contexts, and iterative involvement in the design process. It also emphasizes holistic attention to the user experience and promotes multidisciplinary collaboration. Frameworks such as those proposed by Gould et al. [34], ISO 9241-210 [35], and Hassenzahl (2004) [36] underscore the importance of these principles, ensuring that the design process remains focused on the users' needs and experiences. In domains such as scientific visualization, UCD should actively engage domain experts and users. Gould et al. [34] emphasize that a thorough user and task analysis, combined with iterative design, ensures that visualization solutions effectively address real-world needs. This approach is further supported by Boivie et al. [37], who demonstrated that understanding domain-specific challenges leads to refined visualization features aligned with scientific objectives.

2.5.1 Challenges in User-Centered Design

The design of assistive systems faces several key challenges that must be addressed to ensure inclusivity and usability for a diverse user base. These challenges can be broken down as follows:

- **Accommodation Problems:** These issues arise when users with different needs interact with the system. For example, people with hearing impairments may require different accommodations compared to those with visual impairments or mobility challenges. A well-designed assistive system should accommodate all user demographics.

- **Navigation Performance:** Navigation performance refers to how quickly a user can interact with the system and reach their goals. It plays a significant role in improving the user experience. To address this challenge, UI design must evaluate navigation performance while ensuring that it meets user needs.

- **Display Unit Resolution:** The display quality is critical for conveying information effectively. It should be clear and readable, balancing visual clarity with the computational cost to ensure usability for all users.

- **Ergonomic Considerations:** Ergonomics are fundamental in ensuring the usability of any assistive system. The system should be designed to minimize repetitive strain, enhance safety, and optimize comfort. Particular attention should be paid to the design of portable devices, keyboards, and work environments to accommodate the physical characteristics of different users.

2.5.2 Stages of the User-Centered Design Process

The UCD process consists of three primary stages: user and task analysis, iterative design, and full realization. These stages ensure that the design is user-focused, effective, and fully meets user needs. The stages can be outlined as follows:

- **User and Task Analysis:** The user and task analysis stage focuses on understanding user needs and defining clear goals through comprehensive domain analysis. This process begins by identifying the target audience and gathering information about user demographics, capabilities, preferences, and familiarity with similar systems. Collaborative working sessions with domain experts are conducted to explore workflows and challenges while educating participants about available visualization techniques and system functionalities. Demonstrations of potential solutions or prototypes are then presented to users and stakeholders to gather feedback on usability and task-specific difficulties. These activities encourage collaborative problem-solving, allowing designers to prioritize user needs based on their criticality and impact on the overall experience. For example, in developing visualization tools for combustion scientists, discussions revealed the need for efficient particle extraction in post-hoc analysis, guiding the design process to address domain-specific requirements [38].

- **Iterative Design:** In this stage, prototyping is used to explore potential solutions. Feedback from users is collected and used to refine the designs. Techniques such as sketching, mock-ups, and digital prototypes help test ideas quickly and align them with user needs. For example, the development of a PDF-based analysis tool for combustion simulations led to major shifts in design direction, prioritizing statistical analysis capabilities based on iterative user feedback [38].

- **Full Realization:** This stage involves the implementation of the design and comprehensive usability testing, which includes both user experience evaluations with visualization experts and domain-specific testing with end-users [37]. This step ensures the visualization meets both functional and experiential goals, enhancing its practical value for end-users, particularly within scientific communities.

2.5.3 Expanding User-Centered Design to Multi-User Contexts

The rise of social and collaborative technologies has necessitated the evolution of traditional user-centered design approaches into Multi-User Centered Design (MCD). MCD extends the principles of UCD by emphasizing the social and collaborative dimensions of user interactions, particularly in group settings. This approach considers factors such as diversity in user profiles, social presence, and how effectively a design meets user expectations in multi-user contexts ISO 9241-210 [35].

A key aspect of MCD is accounting for a diverse range of user profiles. Collaborative systems often involve users with varying ages, cultural backgrounds, expertise levels, and interaction preferences. These differences must be reflected in the design process to ensure inclusivity and accessibility. Additionally, fostering social presence—the sense of being aware of and connected to others—requires thoughtful design of features such as user representation, communication tools, and shared workspaces.

Evaluation in MCD also differs from traditional UCD, as it focuses on multi-user testing to assess how well designs facilitate social interactions and collaboration. Tools like the Multi-User eXperience (MUX) questionnaire have been developed to capture user experiences in group settings Lee et. al. [39]. Such evaluations highlight the effectiveness of features like shared interfaces, synchronized workflows, and collaborative decision-making mechanisms. Ethical considerations are central to MCD, ensuring that designs promote fairness, inclusion, and accessibility for all users. For instance, Su et. al. [40] emphasize the importance of addressing issues related to gender, age, and disability to create equitable and user-friendly solutions.

By addressing these aspects, MCD complements and expands upon UCD, making it more relevant for contemporary collaborative environments. This approach ensures that the resulting systems not only meet individual user needs but also support group dynamics and social interactions, thereby providing more comprehensive and effective design solutions.

2.5.4 User Stories

User stories, a UCD method, serve as an agile tool designed to simplify the process of collecting and understanding user needs, providing a clear view of requirements. They are widely used in agile development as they help convert vague needs into more specific and detailed requirements, as mentioned in [41]. User stories generally engage multiple stakeholders, including end users, development team members, and product owners, each with varying levels of domain expertise.

Zacharias et al. [42] outlined customized methods for requirement elicitation in assistive systems using user stories, which include the following steps: (1) User identification and selection, (2) Preparation of requirement elicitation tools, (3) User interaction, and (4) Story analysis and validation. These steps enable the team to create a comprehensive requirement list for product development.

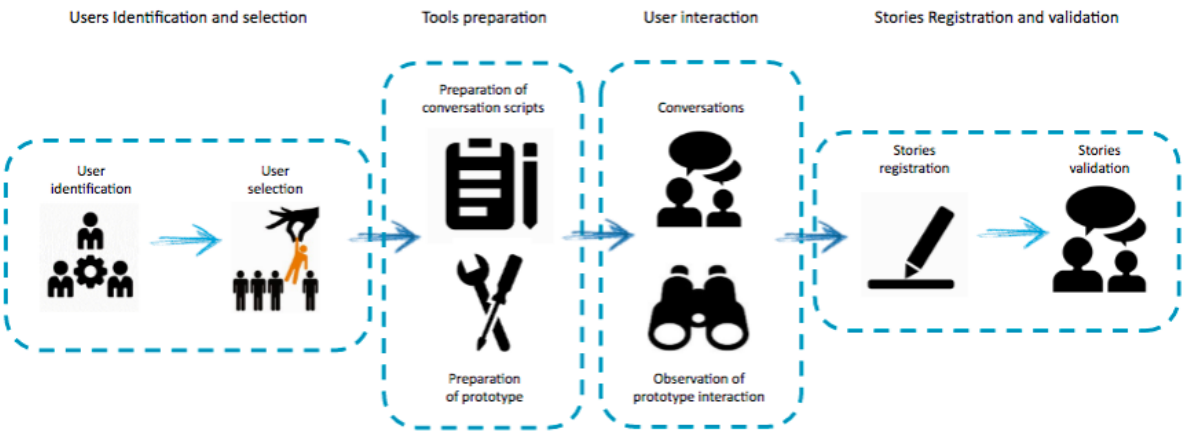


Figure 2.3.: User stories methods customized for assistive systems as mentioned in [42]

2.5.5 Usability

Usability is the degree to which a specific goal can be accomplished effectively, efficiently, and with maximum user satisfaction within a particular context [43]. Usability plays a key role in influencing user satisfaction, reduction in frustration, effective communication of information reducing errors, improved production performance, and also user engagement and experience. Rezaeiet et. al. [44] identified three primary challenges in incorporating usability-based design considerations for operators: specific target user groups, specialized user interfaces, and interdependency issues. The study also highlights three critical factors influencing application usability: time, efficiency, and cost. Furthermore, the paper presents a new perspective on system usability by dividing and analyzing the UI architecture design process across three interdependent domains: User, Need, and Application spaces.

1. **User Space:** This refers to the characteristics and diversity of the target user groups, categorized based on factors i.e., age, culture, knowledge level, gender, and health conditions. This is critical for the development of the solution for ensuring that the system is accessible and inclusive, particularly for workers with disabilities.

2. **Need Space:** This identifies user requirements by focusing on the assistive system's intended behavior, i.e., the primary objective the system aims to achieve, thereby guiding the design process to address specific challenges like user experience, user satisfaction, and enhancing efficiency.

3. **Application Space:** This encompasses solutions from various domains designed to deliver fast and reliable responses to interaction modalities. This space helps benchmark and integrate complementary interfaces—such as digital displays, and pick-by-light systems—to provide a multimodal, user-centered solution.

Together, these spaces not only streamline the research process but also ensure that the developed system is well-aligned with both user needs and the technical demands of modern industrial environments.

2.6 Accessibility

Accessibility refers to the degree to which a system accommodates the diverse needs of its users, ensuring that individuals with varying abilities can interact with and benefit from digital content. As inclusivity becomes a core principle in user interface (UI) design, accessibility has emerged as a critical factor. Accessibility is characterized by key attributes such as equitability, flexibility, intuitiveness, perceptibility, error tolerance, and minimal effort in use, ensuring that a wide range of users with varying needs can effectively engage with a system [45].

Research from the Disability Rights Commission (DRC) highlights that many websites fail to meet basic accessibility standards. Effective accessibility aids users with special requirements, allowing them to understand, perceive, navigate, and interact with web content more easily. The Web Content Accessibility Guidelines (WCAG) have been instrumental in facilitating these criteria. The WCAG is not only relevant for web interfaces but also applicable to any interface. This broad applicability ensures that accessibility principles can be integrated into the design of diverse digital platforms, thereby supporting inclusive design practices. According to Harper et. al., the guidelines aim to enhance web accessibility, though their implementation remains a challenge due to the optional nature of the standards, the lack of enforcement, and testing difficulties [46]. The Web Accessibility Initiative (WAI), which supports the WCAG, also provides further guidelines to enhance accessibility across the web. However, challenges persist in ensuring uniform adoption of these guidelines, given their voluntary status. The guidelines themselves are divided into two primary themes to help integrate them seamlessly into user interfaces they are mentioned as follows:

The first theme, ensuring graceful transformation, emphasizes the ability of content to adapt and transform across different platforms and devices. This includes ensuring that content remains accessible, understandable, and navigable, regardless of how it is presented. The second theme, making content understandable and navigable, focuses on simplifying and clarifying content to ensure that users can easily comprehend and navigate it. Together, these themes cover both the technical aspects of content transformation and the importance of clarity in design.

No.	Web Content Accessibility Guideline
Theme 1: Ensuring graceful transformation	
1	Provide equivalent alternatives to auditory and visual content.
2	Do not rely on color alone.
3	Use markup and style sheets properly.
4	Clarify natural language usage.
5	Create tables that transform gracefully.
6	Ensure pages featuring new technologies transform gracefully.
7	Ensure user control of time-sensitive content changes.
8	Ensure direct accessibility of embedded user interfaces.
9	Design for device independence.
10	Use interim solutions.
11	Use W3C technologies and guidelines.
Theme 2: Making content understandable and navigable	
12	Provide context and orientation information.
13	Provide clear navigation mechanisms.
14	Ensure that documents are clear and simple.

Table 2.2.: Summary of the Web Content Accessibility Guidelines (WCAG 1.0)

2.6.1 Innovations and Academic Efforts in Accessible Technologies

In recent years, there has been significant progress in the integration of accessibility into software design, driven by innovations in technology, evolving design principles, and increased awareness of inclusivity. This shift has been particularly evident in the fields of User Experience (UX) and human-computer interaction (HCI). Companies have introduced groundbreaking technologies to address the needs of users with disabilities. For instance, Facebook's Automatic Alt Text generates image descriptions for blind or low vision users [47], Amazon's 'Show and Tell' feature for Alexa helps visually impaired users identify objects via the Echo camera [48], and Microsoft's Xbox Adaptive Controller accommodates gamers with mobility impairments [49]. These advancements not only reflect the tech industry's commitment to inclusivity but also help companies comply with accessibility regulations, such as the Americans with Disabilities Act (ADA), while contributing to a more equitable digital landscape [47].

Academic institutions are also playing a crucial role in promoting accessibility. Initiatives such as Teach Access advocate for integrating accessibility-related competencies into computer science and HCI curricula [49]. Educational programs have begun incorporating accessibility principles to prepare future developers for designing inclusive technologies. For example, El-Glaly et. al. developed a software engineering course focused on enhancing student's understanding of accessibility [50], while Kelly et. al. proposed educational modules for high school students to increase awareness of accessibility in technology design [51]. Gabbert et.al. emphasized the importance of introducing accessibility concepts in introductory CS courses [52], and the REDi Program at Carleton University has pioneered research and education in accessibility design [53]. These academic efforts ensure that accessibility becomes an integral part of technology education and development.

Inclusive design, also referred to as universal design, serves as a key principle in achieving accessibility. By adhering to principles such as equitable use, flexibility in use, simple and intuitive navigation, and tolerance for error, designers can create interfaces that cater to users with diverse abilities, including those with visual, auditory, cognitive, and physical impairments [54]. Techniques like alternative text for images, keyboard navigation, and media captions ensure that digital platforms are accessible to all users. Together, these innovations, academic initiatives, and design principles highlight a growing commitment to inclusivity in technology, fostering a more accessible and equitable digital environment.

2.6.2 Challenges and the Future of Inclusive Design

Despite considerable progress, challenges remain in implementing inclusive design, particularly with existing technologies. Legacy systems, technical constraints, and limited specialized software can make it difficult to retrofit interfaces to meet accessibility standards. Additionally, the cost of implementing accessibility features, including hiring specialists and investing in assistive technologies, can be prohibitive for smaller organizations. Moreover, limited awareness and training in inclusive design practices among designers exacerbate these challenges, leaving many unaware of how to effectively create accessible interfaces [48]. However, the future of inclusive design looks promising with the advent of artificial intelligence and machine learning, which have the potential to create adaptive and personalized interfaces for individual needs [48]. Collaborative efforts with disability advocacy groups will be crucial to ensuring that inclusive design practices continue to evolve and meet the needs of all users.

In total, it is also essential to consider the ethical and social aspects of incorporating assistive systems, as these factors can serve as either goals or constraints, depending on the context. Such considerations should be treated as 'design considerations' during the initial stages. To ensure these technologies are fair, beneficial, and free from unintended harm, several ethical considerations must be addressed [55].

Key ethical considerations in such scenarios include ensuring data security and privacy, obtaining clear consent for data collection and use, and maintaining transparency with participants. Other important ethical considerations include:

The implementation of assistive systems demands a multifaceted approach that encompasses both technical and social considerations. On the technical side, it is essential to implement robust data privacy measures and enhance employee autonomy by designing systems that support workers without rendering them overly dependent on technology—thus ensuring that critical skills and decision-making capabilities are preserved [56]. Equally important is ensuring that the algorithms driving these systems are free from biases, providing equal access for all employees regardless of role, gender, age, or any other characteristic. Moreover, transparency regarding how these systems operate, including their limitations and potential risks, must be maintained alongside established mechanisms for accountability in the event of system failures or errors. Given the potential impact on employment, the aim should be to use technology to augment human capabilities rather than replace workers, while also offering opportunities for skill development and adaptation to evolving job roles. Socially, the integration of assistive systems contributes to enhanced occupational safety through increased automation, better ergonomic design, and improved collaboration. It also necessitates careful consideration of legal regulations and liability issues, as well as the impact on job roles and responsibilities during transitional periods. Furthermore, fostering a culture of acceptance and trust in new technologies, building a sense of community within the workplace, engaging local community stakeholders to ensure that technological advancements benefit the broader society, and aligning the implementation with corporate social responsibility goals are all critical to ensuring that assistive systems are both effective and ethically sound.

Chapter 3

Literature Review

A literature review has been conducted to explore current trends and approaches in assistive systems for creating inclusive and optimized production setups. The literature have been derived and selected based on the Prisma flow approach, these scientific publications have been reviewed, evaluated, and methodologies to develop inclusive production assistance systems for people with special needs. The detailed procedures for the literature review are described in the following sections.

3.1 Review on Existing Work

The current focus of the literature is to determine all the considerations and incorporation for the development of assistive systems that are both inclusive and intuitive of the users in production setup, while also optimizing the process. The review was formed on the 1st of October 2024. The review was intended to be widespread and international. Hence 'Google Scholar' and 'Research Gate' were used due to their free access and availability of many scholarly articles. The literature was derived from the article search by using the search strings:

('methodology' OR 'method' OR 'evaluation' OR 'development' OR 'design' OR 'technique' OR 'approach' OR 'procedure' OR 'plan' OR 'inclusive' OR 'intuitive' OR 'optimization' AND 'Production' OR 'manufacturing' OR 'assembly' AND 'worker assistance' OR 'assistive systems' OR 'operator assistance' OR 'cognitive assistance system')

A filter for not including the thesis works, books, posters, and preprints were included. To maintain the relevance of the literature review to the latest trends and industrial practices the results were further narrowed down to the literature since 2020. This resulted in a considerable reduction in documentation leading to a more focused study. The papers from both research databases were screened through title and abstract for literary relevance and 22 papers were shortlisted as relevant based on competency. The exclusion criteria for the literature review were as follows:

1. Assistance systems focused on physical support, though important, are not the primary focus of this study.

2. Studies lacking direct applicability to the manufacturing sector and were excluded.

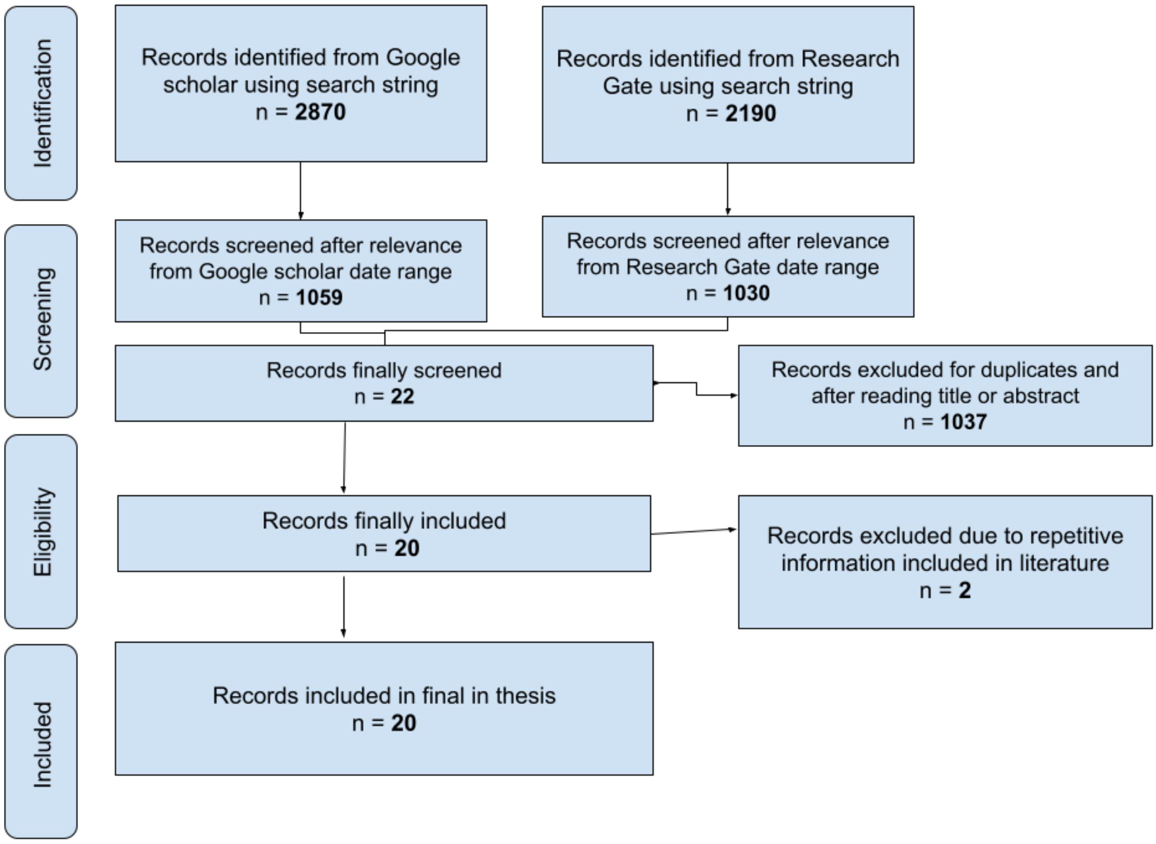


Figure 3.1.: PRISMA literature flow chart

The figure above (3.1) provides a visual representation of the standardized process for literature identification, screening, determining eligibility, and final inclusion in the review and state-of-the-art documentation. There was considerable forward and backward citation tracking due to the quality of relevance of the work. Backward tracking identified foundational studies, while forward tracking uncovered recent high-quality research expanding on these works. Together, these methods provided a balanced selection of influential and contemporary studies.

3.1.1 State of the Art

In recent years, the growing demand for a highly customizable product range has increased the integration of assistive systems in manufacturing. These systems support manufacturing tasks by reducing cognitive stress associated with memorizing customized designs or considerations and providing product-specific instructions, solutions, or training. As a result, new-age assistive technologies that offer flexibility, such as data visualization, and interaction systems have become highly valuable [57]. This trend has also fostered the adoption of human-centered design approaches for developing assistive systems in industrial settings.

Customization of products is essential to accommodate individual user needs and enhance accessibility and user experience. To deliver truly tailored solutions, workers require access to context-sensitive information that provides meaningful, task-relevant data precisely when it is needed, thereby enabling efficient task execution and informed decision-making. Froschauer et al. [1] underscore the importance of employing a contextual design methodology—a structured framework for planning and implementing human-centered designs—to capture and analyze this critical information. By integrating *contextual inquiries* and *contextual analysis*, this methodology effectively processes, organizes, and interprets user data, ensuring that the information provided is both relevant and timely. As a result, the approach not only informs product customization but also significantly enhances the overall user experience.

Similarly, Quandt et al. [7] highlight the significance of human-centered design throughout the product lifecycle of cognitive assistance systems. This approach is based on the standardized process model outlined in ISO 9241-210 and emphasizes intuitive UI design, enhanced user involvement, and the application of principles proposed by Gould et. al. [58]. Additionally, the process incorporates workplace ergonomic design considerations as per ISO 6385:2016, which details the steps required to achieve a human-centric design process across various stages of the product lifecycle.

In most studies on the design and implementation of assistive systems, a key focus is maintaining a user-centric perspective, which aligns with the findings of Börold et al. [59]. The primary objective of their work was to reduce the cognitive load on workers. The study advocates for the use of multimodal interaction systems, which lower cognitive demands by providing multiple interaction methods, such as voice commands and graphical interfaces. The users were categorized based on factors such as their experience, prior knowledge, and frequency of interaction with the task or technology.

Similarly, the study by John [60] delves into the cognitive effects of UI design principles that are critical for developing intuitive interfaces. By applying theories such as Miller's law—which limits the number of items an average human can process simultaneously—alongside the split attention effect occurs when users must divide their focus between disparate but related sources of information, which increases cognitive load and hinders effective processing. In contrast, the redundancy effect arises when the same information is presented multiple times in different formats, potentially overwhelming users and impairing their comprehension. The research provides concrete guidelines for minimizing cognitive overload. These principles inform the creation of UIs that streamline information presentation, reduce unnecessary complexity, and improve overall user interaction.

Building on the discussion of interaction technologies, Burggräf et al. [61] present an empirical analysis of adaptive assembly systems, highlighting their situational awareness capabilities. Adaptive assembly systems refer to manufacturing setups that dynamically adjust assembly processes in real-time based on various inputs such as worker performance, environmental conditions, and product customization requirements. By leveraging digital technologies, and sensor data these systems can tailor instructions and resource allocation to optimize efficiency and accommodate the diverse capabilities of the workforce. These systems enable quick, informed responses in highly customizable products and flexible working environments, which ultimately result in an increase in product variants. Adaptive assistive systems capable of real-time adaptability are highly situationally aware of the task at hand and combine the quality and cost advantages of both earlier highly automated systems and the present area of interest to explore the innovative thinking of humans through their cognitive abilities to achieve efficiency. The study also surveyed on the current trends in (1) the technological status quo. The findings that 94% of workers utilize screen-based visualization systems, while more advanced technologies like augmented and virtual reality remain underutilized, especially in smaller industries. (2) Flexibility in assembly: they noted that almost 63.6% of the users found flexibility to be highly important, 32.6% as important, and only 3.1% of them rating flexibility less important. (3) Cognitive assistance during assembly and worker qualification, lastly (4) Worker acceptance and related factors influencing the adoption of adaptive assembly systems. Finally, it summarises the importance of considering cognitive loading while designing which is the main cause of almost 58% of errors due to unbalanced cognitive loading.

Horn et al. [62] propose a framework to enhance worker engagement to address these challenges by proposing a framework to enhance worker engagement through assistive technologies. Their work emphasizes incorporating the "voice of the worker" into human-centric production systems to improve engagement and productivity. The study also provides a possibility of not being able to receive meaningful data from the worker, due to many potential explanations characterized by power imbalance, and higher uncertainty. They propose practical guidelines based on 8 principles for practitioners to align employee needs with organizational goals, reinforcing the role of assistive systems in supporting workers based on 3 main levels (1) Before integration of the assistance system, (2) during, and (3) after. They have a methodological approach to gain complete insight for further research by using secondary interviews, commercial industry reports, workshops, and informal interviews.

The effectiveness of Cognitive Assistance Systems (CAS) is examined extensively in various studies. Fink et al. [63] investigates the widespread use of CAS in German manufacturing, such as display screens and pick-by-light systems, demonstrating that CAS significantly reduces cognitive demands and improves assembly quality and productivity. The cognitive assistance systems were divided into stationary (pick-by-light, pick-by-voice, integrated screens, displays, tablets, and projectors), mobile (smartphones, tablets, laptops), and wearable systems (mixed reality headsets, intelligent gloves, head scanners) [64]. Fink also verified various effects of the cognitive assistance system's context of the industry's success such as their social economics, learning aspects, quality aspects, and productivity aspects. The study concludes that cognitive assistance systems significantly improve stability in German manual assembly, especially in automotive, mechanical, and electrical engineering industries. Key socioeconomic benefits include enhanced recording of assembly steps, though training and quality improvement effects are statistically limited. Productivity gains are evident, as cognitive systems stabilize processes and reduce cognitive stress, supporting efficient task performance.

Lucchese et al. [65] provide further evidence of the positive impact of pick-by-light systems, showing that they enhance task performance by leading to fewer picking errors, higher productivity, reduction in task completion time and reduced workload in assembly and picking tasks. The study hypothesized that fully assistive cognitive technologies would outperform semi-assistive options in both performance and perceived workload, particularly in reducing cognitive strain factors like frustration, effort, and mental demand. They employed methods of task completion times and post-experiment ad-hoc questionnaires. The results of these findings supported this hypothesis, showing that fully assistive technologies, such as pick-by-light, led to faster task completion times and significantly lowered perceived workload in areas of mental demand and frustration, especially in order-picking tasks. In assembly tasks, fully assistive systems reduced cognitive load, though their impact on overall workload and physical effort was less pronounced. These results confirm that fully assistive technologies offer distinct advantages over semi-assistive options, particularly in enhancing performance and easing cognitive demands in manual industrial tasks.

Similarly, Hercog et al. [66] explore the development of a pick-to-light system integrated with computer vision, which significantly improves training times and worker satisfaction. The paper insists on an additional aid to the order picking a PC with a touchscreen to visualize and interact with the production process. The work also explains in detail the development of a pick-by-light module, including system architecture, and hardware considerations (ESP-32 microcontroller), software programming using event structure in the LabVIEW development environment, communication protocol, and firmware. The study depicts the integration of 16 PTL modules, but the suggested approach could be scalable, and can easily be upgraded to add more modules. They also proposed a systematic approach for ergonomic improvement Self-adaptive Smart assembly system (SASAS) which enhances ergonomic conditions by using two axes easy-access fast-picking area and a third axis for worker area height reconfiguration, as evaluated using the Rapid Entire Body Assessment (REBA) analysis framework.

While cognitive assistance systems offer numerous benefits, Peltokorpi [67] explores their impact on workers with cognitive disabilities, highlighting the importance of reducing cognitive load through tailored instruction methods, ranging from paper-based to adaptive projection systems. They also noted the different types of cognitive loading as discussed in [68] as extraneous, intrinsic, and germane loads. Intrinsic loads are the cognitive load created due to the natural complexity of the tasks. The interacting elements of the intrinsic cognitive loading cause germane loads. They tried to verify the effectiveness of cognitive assistance technology in employee training as the difficulties of cognitive disabilities are due to a higher demand for cognitive processing, attentional processes, and distractions. They employed learning rates for different problems using a standard Wright's learning curve, which is further modified to accommodate complex variables. They also discussed about four forms of effective instructions paper-based, animations, projection, and adaptive projection, and evaluated the experience levels of these instructions. They also classified the experience and the instruction effects based on cycle times into initial learning, plateau, and retention levels.

Bendzioch et al. [69] support the findings, comparing traditional paper-based methods with cognitive systems and noting that while cognitive systems reduce assembly errors, their impact on productivity is mixed. They note the existence of common incompatibilities in the information transferred from the source to the user, often referred to as 'deficits' or 'gaps'. These issues are highlighted through a model of human information processing, as discussed by [70] and [71]. These gaps were differentiated; (1) Gap 1 missing data, (2) Gap 2 wrong data, (3) Gap 3 imperceivable data, (4) Gap 4 complicated data, (5) Gap 5 routine error, (6) Gap 6 no feedback from system, (7) Gap 7 forgetting information, and (8) Gap 8 difference in experience. The study also highlights the new-age assembly assistance system, *RICOH SC-10A*, which utilizes image processing to provide error feedback and execution instructions.

Addressing the needs of an aging worker, Mark et al. [72] propose a design methodology axiomatic design for integrating assistive systems into workplaces to accommodate older workers and those with disabilities, enhancing both mental and physical well-being by deducing customer needs and constraints to generate functional requirements and design parameters, along with considering physical variables for ergonomic improvement. The study also develops a prototype to generate digital work instruction through projection systems along with popups, counters, timelines, and a signaling system to signal the operations supervisors' assistance requirement.

The challenges associated with assistive systems are also notable. Michael et al. [73] explore the difficulties in creating reusable software components for cognitive assistance systems, noting that variations in user interfaces and contextual information make achieving reusability difficult. To overcome shortcomings in reusability in current systems the work suggests using behavior and context models. It suggests a generative assistance system to replace outdated instructive manuals that become outdated when the production setup is subjected to even minute changes. The work also mentions challenges that have to be overcome to establish assistive systems in the production domain; insufficient relevant context information, high heterogeneity of user interface, adaptability to personal needs, and privacy needs. Pimminger et al. [74] also highlights the challenges of implementing assistive systems in real-world production environments, where hardware limitations and the need for frequent recalibration often arise when transitioning from lab settings to the production floor. The work also explored predictive models for enhancing cognitive assistance systems.

Precup et al. [75] propose a novel approach using Markov models to predict worker actions in assembly tasks, enabling assistive systems to provide more efficient guidance and reduce errors that enable users to gain a major advantage in conducting production with limited or no training data. The Markov models were assisted by an object detection model using YOLOv5 and Microsoft HoloLens-2 and an assembly information model.

Haase et al. [76] offers a critical perspective on the potential risks of over-reliance on assistive systems. They caution that while these systems can empower workers by providing necessary support, poorly designed systems may undermine worker autonomy and lead to skill degradation. It is, therefore, essential to design these technologies in ways that encourage learning and personal development, rather than merely automating tasks. The work expresses the needs of employees in the workplace during unforeseen circumstances by considering the existing ironies of automation. They suggest a unique approach to the methodological development of an assistance system to promote learning by considering influencing parameters for design objectives. To generate the design objectives the study considers the activities in their representational character functions as a connection between individuals and organizations based on activity theory [77] and activity theoretical basic model to generate interrelations and dependencies of the learning activity system to provide important information on influencing variables.

Patrick et al. have documented in their work [78] the trend of incorporating artificial intelligence tools to develop effective assistance systems. These systems enable both machines and humans to access and interpret the complex data generated by smart factories, thereby allowing them to react appropriately to evolving operational conditions. This work also deals with the advantage of cross-functional cooperation and networking as a key requirement for data exchange and benefiting from AI tools in an industrial setup. They attempted to study all the notable cognitive assistive systems for assembly processes including; For example, vision-based systems like the Augmented Workplace from the motionEAP project leverage camera-based recognition to trigger multimodal instructions—such as projections and bin-picking assistance—that guide workers through assembly tasks. In another group, mobile and context-aware solutions such as Plant@Hand integrate displays, sensors, and software assistance to provide real-time step documentation, next-step prompts, and error detection through both textual and graphical cues. Finally, integrated systems like Bosch Rexroth's ActiveAssist combine multiple modalities (e.g., pick-by-light, projection, and Radio Frequency Identification (RFID)) with connectivity to Management Execution System (MES)/Enterprise Resource Planning (ERP) systems, thereby seamlessly merging advanced AI-driven functionalities with traditional assembly processes.

Chapter 4
Methodology

The methodology section of this thesis outlines the research approach and methods employed to address the primary objectives and research questions of the study. It includes a comprehensive overview of the research design, encompassing prototyping, requirement elicitation, and user stories. The section details the insights and user needs about the assistive systems which can be generated from surveys, interviews, or focus groups. It also explains the sampling strategies and criteria used to narrow down the target audience.

Additionally, this section also makes considerations for methodologies chosen to maximize the reliability, accuracy, and objectivity of the assistive system for inclusive production, while also considering any ethical and social considerations, such as participant consent, data privacy, and confidentiality. The section concludes with a discussion of the limitations and potential biases of the chosen methods, ensuring a transparent and critical approach to the research process.

4.1 Requirement Elicitation

In designing and developing an assistive system using UCD principles, the most important step is to involve users in product development and gain an understanding of the user expectations on the requirement of the product. Requirements are the characteristics of a product or service that define various criteria for its acceptance and usability. They can be categorized into functional and non-functional requirements. Functional requirements are the specific capabilities of the assistive system to assist the user in performing tasks, improving accessibility and user independence. Non-functional requirements specify the quality attributes of the assistive system to ensure its effective, reliable, and user-friendliness of the system. Requirement elicitation is a crucial process of UCD approach, characterized by iterative improvement during the development process through result revaluation and validation with stakeholders [79].

The process of iterative requirement elicitation by following the user stories method is described in the table 4.1 as shown follows.

Product Deployment	Wien Work
User Identification	Assembly workers with hearing impairment
	Assembly workers with other disabilities
	Assembly workers without any disabilities
Requirement elicitation tools	Focus group questionnaire and interaction script
	Prototype preparation
User interaction and data collection methods	Use of scripts for conversation
	Audio recording of user interaction
	Observations of prototype use
	Video recording of user interaction and prototype use
Requirement generation using user story validation	Identify Functional Requirements
	Identify Non-Functional Requirements
	Refining and classifying requirements based on priority

Table 4.1.: Requirement elicitation steps following User story method

4.1.1 Insights for Requirement Elicitation from the Literature

The literature has provided several valuable insights for considerations to be made to develop an effective instruction assistive system in a production setup. To address these issues that are mentioned in the work earlier. The following requirements have been derived based on the literature, which can be subjected to improvement through user feedback. The initial requirements are as mentioned follows:

1. Identification and development of an assistive system to accommodate workers' diverse needs in manufacturing setup as discussed in section 4.4.
2. Ensure inclusion of diverse user groups to accommodate the entire target audience.
3. Incorporate all intended functionalities comprehensively and effectively.
4. Identify and implement the most appropriate modalities of interaction for the application.
5. Integrate all required usability and accessibility principles, as discussed in section 2.5.

6. Consider all ergonomic factors during the deployment of the assistive system.
7. Address ethical considerations, including privacy, data security, and related concerns.
8. Consider social factors such as preventing overreliance on the system and preserving the critical skills and decision-making abilities of users.
9. Ensure the effective integration of the assistive system within the production workflow.
10. Provide adequate training, troubleshooting tutorials, and guidelines to support users.

4.2 Target Audience

The thesis focuses on the development of assistive systems to aid humans in industrial environments. To investigate the research questions, a case study was conducted, targeting technicians in the assembly process at the Wien Work's 'Holztechnik' department as the preliminary audience. Holztechnik employs individuals with disabilities to provide equal opportunities, and the study aims to address additional disabilities or requirements of these audiences. A secondary audience comprised supervisors at Holztechnik, extending the application to accommodate the diverse user base of the system.

A total of five male participants took part in the study, with the small sample size reflecting the company's scale. The participants represented various age groups: two were aged 26–35, one was 35–40, and one was in the 40–50 range. It was observed that two users in the Endfertigung (Job Finishing) suffered from hearing disabilities. The supervisors, however, did not have any disabilities; one oversaw all production activities and quality inspections, while the other handled planning tasks. The participants had varying levels of experience, ranging from 1 to 8 years.

All participants agreed on the following points: they were required to regularly acquire new skills and were comfortable learning and adapting to new manufacturing technologies. However, they were unfamiliar with assistive systems designed to complement human abilities in manufacturing.

4.2.1 Initial Survey

The first iteration of with the target audience was to identify the target groups for the case study and gain insights into the processes, and standard practices. The basic workflow throughout the factory hierarchy, the source of instruction generation, training, and skills being developed and fostered for the assembly process. The survey was held at the Holztechnik department of Wien Work in a quiet and isolated room to avoid external disturbance and the influence of other workers. The entire discussion was moderated by one of the supervisors at Wien Work to facilitate smooth interaction and easy information conveyance.

Group	Number of Participants	Role in Company
Group 1	2	Supervisors
Group 2	3	Finishing Technicians

Table 4.2.: Initial Survey

The survey was properly recorded and documented. Furthermore, to guide the survey, directional questions relevant to the agenda were formulated and enquired about in relevant situations.

- **Demographic data:** The Demographic data is very essential for understanding and analyzing the diversity of the focus group, enabling clearer insights into the key information of the target audience's background and needs. Several details were collected such as Age, Gender, experience, disability, and special needs.

- **Professional experience and roles:** Professional experience and roles questions help in understanding their roles, and help identify responsibilities, challenges, and expectations for support by asking users to describe their primary responsibilities, the biggest challenges they face, and what types of support they expect from an assistance system, as well as their concerns about system integration, prior experience with similar technologies, anticipated impact on productivity, preferred training methods, and desired level of autonomy with the new system, ensuring the assistance system aligns with their needs and enhances their workflow.

- **Attitude towards technology:** These questions were directed to get information about the perspective and acceptance of new-age technologies in the workplace. These questions could be directed at improving acceptability and usability in users. The questions covered areas such as perceived usefulness, ease of use, trust, comfort in using these systems, and the willingness to adopt the technology. This insight helps to identify potential barriers and ensure a smoother implementation process.

- **Cognitive loading:** The primary objective of the study was to minimize cognitive load. To access the change of cognitive loading, the NASA TLX form was graded and was determined as mentioned below. The cognitive loading evaluation is conducted once again at the deployment phase, to compare and evaluate the reduction of the cognitive loading. This insight helps in designing a system that complements users' cognitive capacity, promoting efficiency and reducing potential burnout. The questions focused on the current workplace situation, addressing aspects such as mental demand, physical demand, temporal demand, performance, effort, and frustration associated with the present task.

4.3 Systematic Assistance System Selection Processes

Mark and Rauch in their work [80] have proposed a methodology for identifying and selecting appropriate assistance systems for specific scenarios based on their four-step process. They include (1) Workplace and work environment analysis to identify constraints or limitations that may influence the selection of assistive systems. (2) Work task analysis to identify task-related parameters and relevant worker needs. (3) Matching worker needs and relevant workplace factors. (4) Matching the determined parameters to the appropriate assistance systems from the catalog. The complete process of developing an appropriate assistance system is described in the schematic flow chart 4.1.

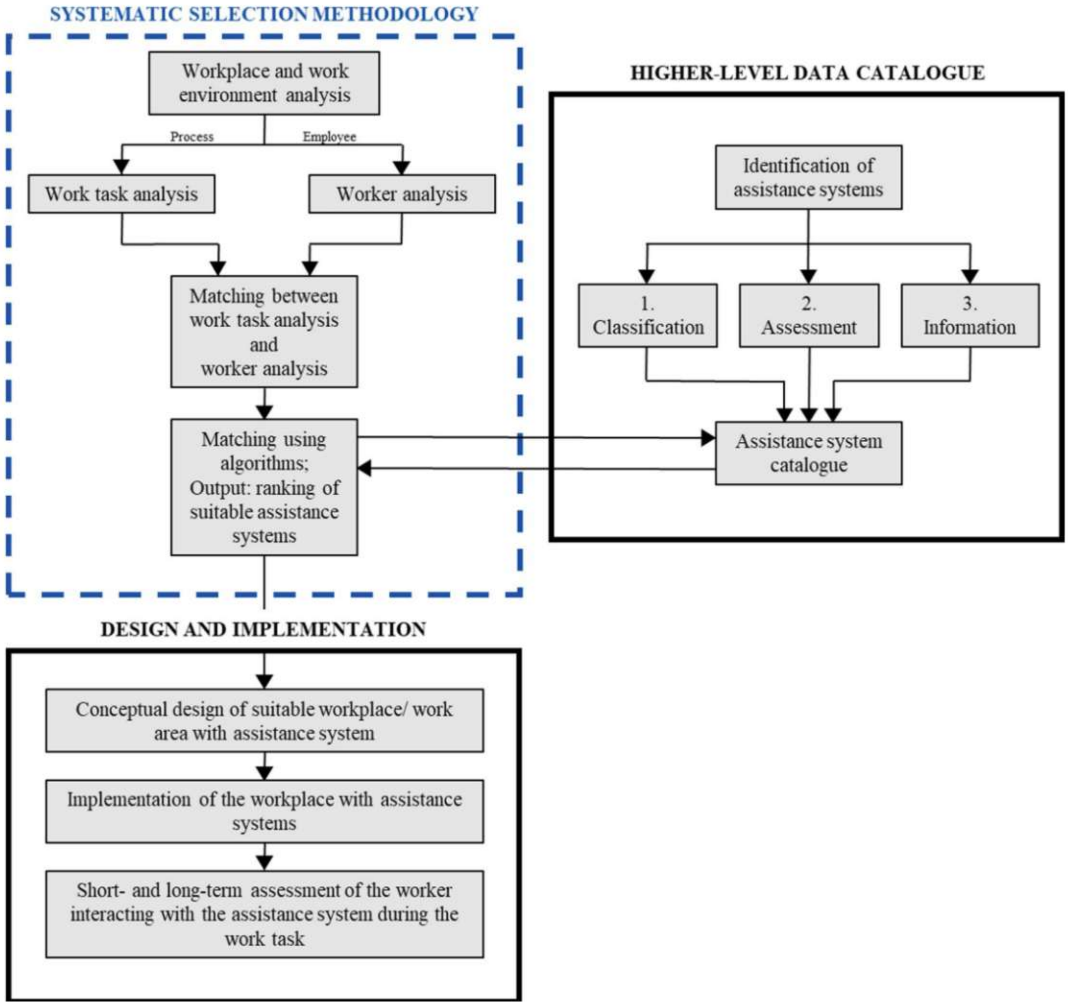


Figure 4.1.: Flowchart representing systematic assistive system selection process [80]

4.3.1 Step 1: Workplace analysis

Figure 4.2.: Image of the workplace for finishing task

In the case of the assembly process in our situation, the assembly process takes place in a designated location as shown in figure 4.2. The worker reviews the job sheet to verify the requirements, selects the necessary items from the bins, assembles the components using power tools, and follows the process until completion. The job sheet does not contain any kind of detailed instruction on carrying out the assembly task. There were no considerations made on the individual ergonomic requirements of the workers. The lighting on the shopfloor is good as the workplace is directly placed in front of the windows, with the noise level within acceptable limits. The power supply and WLAN are available in the location. The user does not have access to any form of assistance system.

4.3.2 Step 2: Work task analysis

The work tasks of the assembly workers were analyzed. The workers were supposed to finish the furniture by installing the necessary components for the finished furniture such as handles, hinges, locks, etc. In order to identify and analyze the specific work tasks requirements of the worker, 23 parameters were derived for general working requirements and were scored on relevance to the present task from a scale of 0 to 1, 1 being ‘needed’, 0.5 being ‘party necessary’ and 0 being ‘not needed’, the encoded parameters form a ‘Relevance Matrix’ (Rx) as shown in the table A.1 This leads to the calculation of the level of assistance required (s) for each work task, as shown in Equation 4.2. The degree of relevance of the work task analysis in this situation results in 47.83 (ref to the equation 4.4).

$$a = \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad (4.1)$$

$$s = \left(\frac{R1 + R2 + R3 + \cdots + Rn}{n} \right) \times 100 \quad (4.2)$$

$$s = \left(\frac{0 + 1 + 0 + \cdots + 0}{23} \right) \times 100 \quad (4.3)$$

$$s = 47.83\% \quad (4.4)$$

4.3.3 Step 3: Worker analysis

The next step is to analyze the worker requirements for assistance systems. Similarly 'Needs matrix' (Nx) is calculated as in the equation 4.5. A scale from 0 to 5 is used, where 0 indicates 'no help needed' and 5 represents 'maximum help needed'. Refer to the table for details A.2 for the calculation of the worker assistance requirement needed. The workers in our case fall into flexible and physically handicapped workers (hearing disability). In this case, we plan to accommodate all the user needs to develop a single assistance system. Hence, the average of the Nx values is considered for the calculation in equation 4.8.

$$b = \begin{bmatrix} 0 \\ 5 \\ \vdots \\ 5 \\ 0 \\ 0 \end{bmatrix} \quad (4.5)$$

$$w = \left(\frac{N1 + N2 + N3 + \cdots + Nn}{n \times 5} \right) \times 100 \quad (4.6)$$

$$w = \left(\frac{0 + 5 + 0 + \cdots + 0}{23 \times 5} \right) \times 100 \quad (4.7)$$

$$w = 42.61\% \quad (4.8)$$

4.3.4 Step 4: Matching work task and Worker analysis

The next step in matching the work task and worker to find a relevant assistance system is to accurately weigh the needs to the relevant requirement. Hence, element-wise multiplication of the Relevance and need matrix is carried out and is represented by the equation 4.9. The final degree of assistance required is defined by the equation 4.10 the degree of assistance required is calculated to be 26.95 %.

$$c = a \cdot b = \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 5 \\ \vdots \\ 5 \\ 0 \\ 0 \end{bmatrix} \quad (4.9)$$

$$r = \left(\frac{(R1 \times N1) + (R2 \times N2) + \cdots + (Rn \times Nn)}{n \times 5} \right) \times 100 \tag{4.10}$$

$$r = \left(\frac{(0 \times 0) + (1 \times 5) + \cdots + (0 \times 0)}{23 \times 5} \right) \times 100 \tag{4.11}$$

$$r = 26.95\% \tag{4.12}$$

4.3.5 Step 5: Matching Requirement Data with Assistance System Catalog

The next step is to compare these combined parameters to the higher-level assistance system data catalog (see appendix **??**). The identification of technologically ready assistance systems available in the market was studied by Mark et. al. [16], Mark mentions in this work that this higher-level catalog is continually evolving. Consequently, the pick-by-light system, identified during the literature review, has been incorporated into the higher-level catalog. The evaluation of the identified assistance system involves an assessment of the so-called Assistance (A_x). The assistance level of the assistance system is marked from 0 to 10 on the level of increasing assistance provided by them. The matrix (M) lists the 23 parameters along the x-axis and the assistance levels of various assistance systems along the y-axis, as outlined in the 'Higher-level assistance system data catalog'. The vector (t) is used to rank the most suitable worker assistance system, as represented by Equation 4.13. The top 5 assistance systems from the vector (t) can be considered for the selection of the assistance system for the situation, which is represented in the table 4.3.

The ranking of the assistance system helps with an overview of the best possible considerations of the assistance system for this situation but is also important to take into consideration other factors for the assistance system adoption, such as the cost of implementation, available space for implementation, ease of use, and other factors [81],[82]. Although the top-ranked projection-based assistance system could address the required needs and relevance of both the work task and the worker in this case, in consideration of additional factors, the second-ranked pick-by-light assistance system could be considered. The chart below 4.3 helps identify the relevant requirements for the work and worker match (blue bar) and the assistance offered by the assistance system (orange bar). It depicts that the pick-by-light system assists with major parameters of requirement such as the *working velocity*, *correctness*, *attention*, *independence*, *responsiveness*, *retentiveness*, *concentration*, *spatial ability*, and *seeing ability*, although it does not provide any assistance for other parameters such as *spatial safety, flexibility, learning ability, ergonomics*, and *dexterity*. To address these additional considerations in the factory setups are being made which is explained further in the section. Hence, the pick-by-light assistance system could be successful in providing sufficient assistance to important parameters for this given case. In addition to the pick-by-light system, an intuitive user interface with relevant information would help improve the usability of the system.

$$t = M \times c = \left[\left[\begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix}\right]\right] \times \begin{bmatrix} 0 \\ 5 \\ 0 \\ 4 \\ 0 \\ 4 \\ 1 \\ 1.5 \\ 0 \\ 0 \\ 1.5 \\ 1 \\ 1 \\ 2 \\ 0 \\ 2 \\ 1 \\ 0 \\ 1 \\ 1 \\ 5 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 73.0 \\ 44.5 \\ 32.0 \\ 71.0 \\ 55.0 \\ 55.0 \\ 55.0 \\ 58.0 \\ 58.0 \\ 59.0 \\ 67.0 \\ 101.0 \\ 99.0 \\ 72.5 \\ 66.5 \\ 25.0 \\ 144.0 \\ 45.0 \\ 9.0 \\ 111.5 \\ 115.5 \\ 11.0 \\ 50.0 \\ 23.0 \\ 77.0 \\ 118.0 \end{bmatrix} \quad (4.13)$$

Ranking	**Assistance system**	**Value from vector t**
1	Projection-based assistance system	144
2	Pick-by-light system	118
3	Laser projection system	115.5
4	In-situ projection	111.5
5	Collaborative Robot	101

Table 4.3.: Assistance system ranking (top 5)

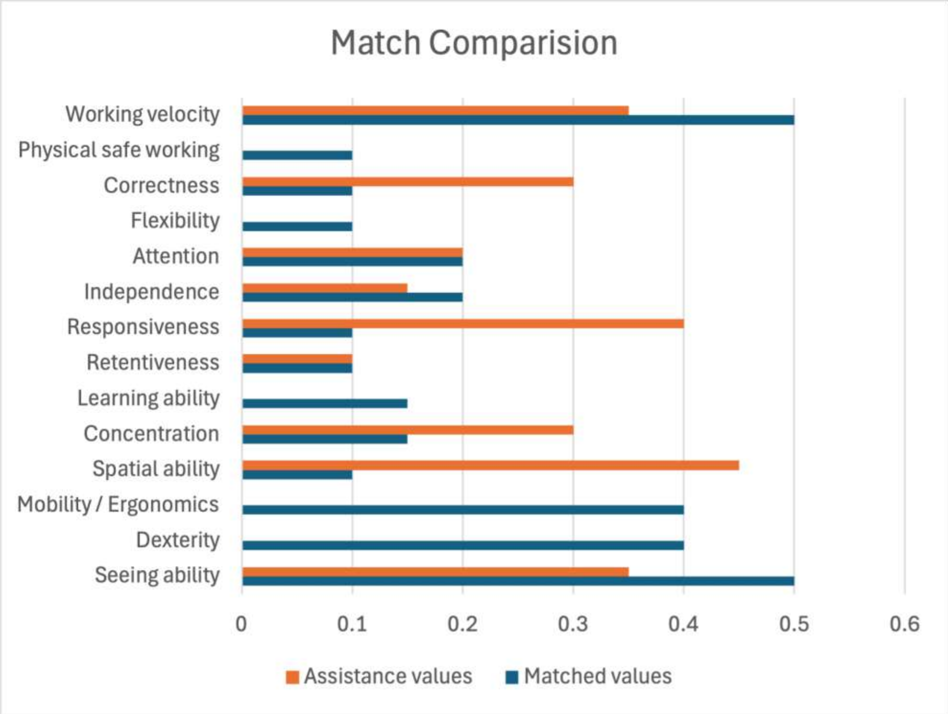


Figure 4.3.: Matching comparison between requirement and the assistant system

4.4 Prototyping

Developing an effective assistive technology for improving an individual's work experience and satisfaction in an industrial setup involves prototyping to clarify requirements, reduce errors, and improve user involvement in product design by iterative modification [83]. This approach improves user satisfaction, user experience, product quality, usability, and functionality.

To build an effective assistive system it is necessary to overcome the problems encountered during the development of assistive systems reducing the interdependencies between the three spaces i.e. user, need, and application spaces. They also categorized users, and clustered them into groups based on their limitations of Degree of Assistance (DOA), to a minimum amount of shared limitations. Due to interdependencies, the cost of addressing these issues grows significantly over time. Therefore, it is more effective to plan, test, and optimize the processes early in the development phase, especially under conditions of high uncertainty and frequent changes, to achieve sufficient process maturity and eliminate major deficiencies with a high level of certainty. Prototyping can be a very remarkable solution in these situations. It also contributes to reducing time to market and time to volume. The process of achieving a highly optimized solution is through repetitive iterations of planning, testing, and optimizing processes and devices early in the stage of development. The prototypes are often partial assistive systems such as low fidelity models / higher level concepts of the system. This approach helps build tailor-made systems with the support of highly experienced personnel from various departments, experts, and stakeholders [84]. In contrast, the final prototypes are constructed just before the project begins, incorporating all the necessary changes. To reach the final prototyping stage, continuous feedback on the process quality from end-users, using methods such as those discussed in Section 2.5.4, would lead to iterative improvements in short cycles. As a result, a high level of general maturity could be achieved earlier, allowing critical issues to be identified and optimization efforts to be concentrated. The final maturity level of the prototype can be determined by considering the following aspects:

1. Operator safety, ergonomics, and workload.
2. Repeatability, accuracy, and resulting product quality.
3. Robustness, susceptibility to human errors, and potential damage to products or equipment.
4. Minimizing non-value-adding actions.

This approach is explained by Rupp and Müller in [12]. This prototyping method of designing and developing an assistive system involves procedures similar to flowchart as shown below 4.4.

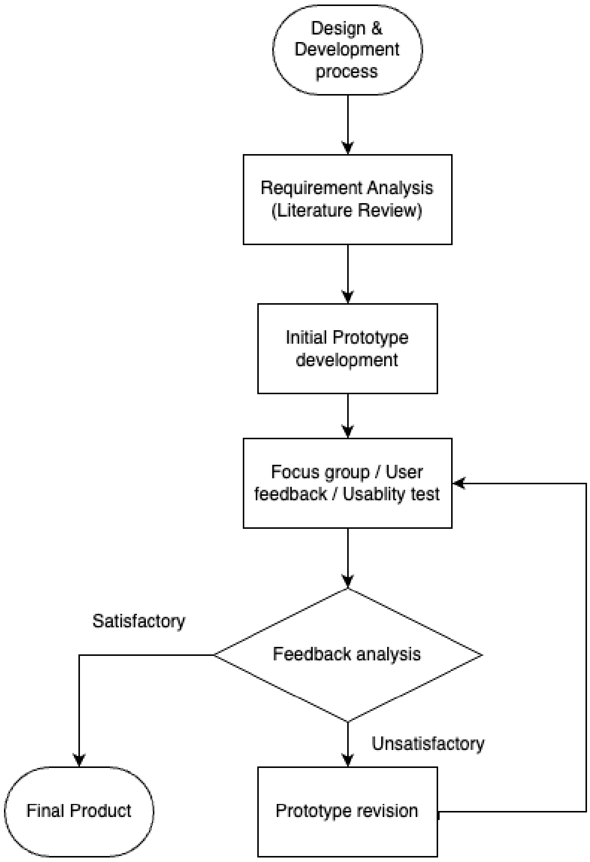


Figure 4.4.: Flowchart for prototype development

4.4.1 Prototype High-Level Concept

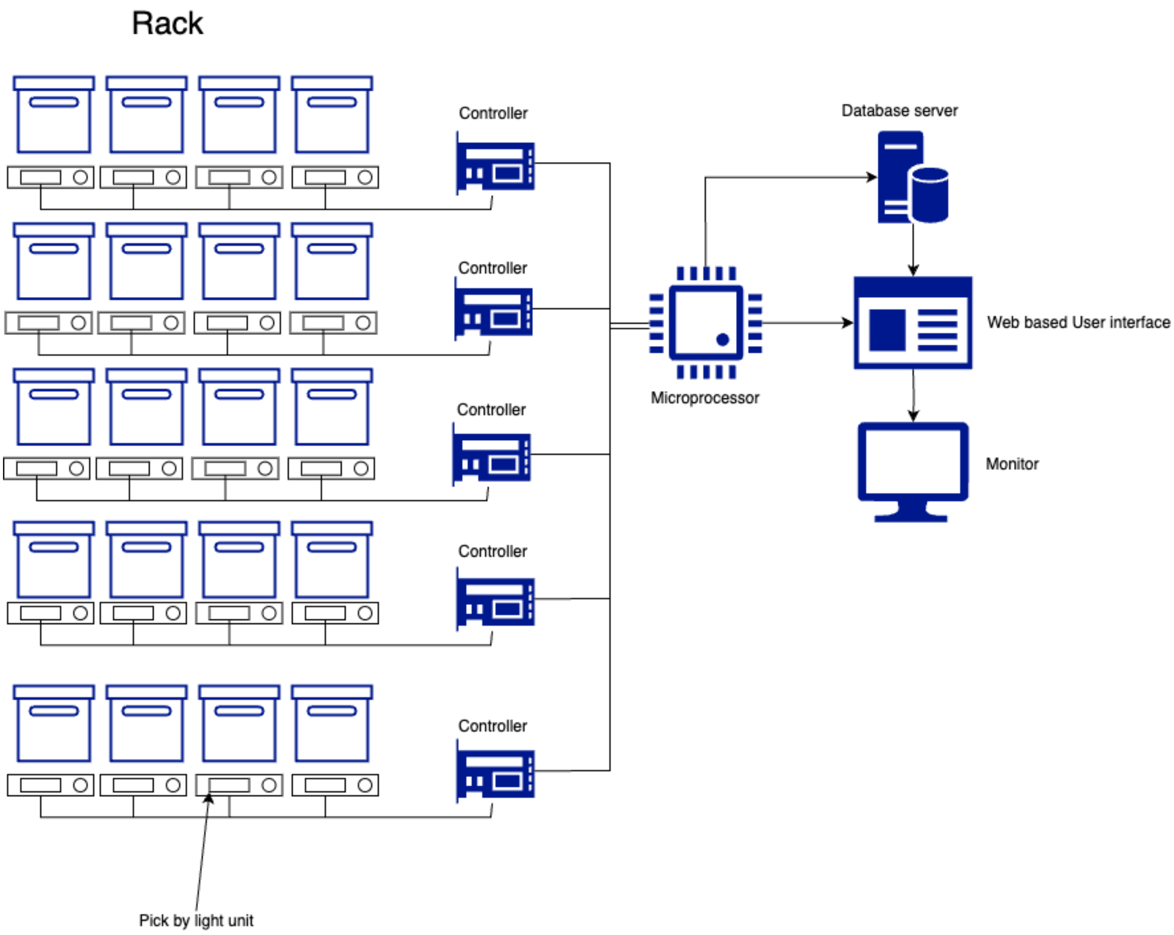


Figure 4.5.: Prototype High-level concept

The high-level concept and overall objective of the prototype in this thesis is to develop an assistive system designed to facilitate the workers to improve inclusivity and adaptivity in an industrial setup taking into consideration the user-centered design approach involving usability and accessibility principles. The core idea of the prototype for the high-level concept utilizes the integration of a web-based application that is intuitive UI setup with a backend database system incorporating the work instruction, work in progress, and other action data alongside a hardware pick-by-light assistive system to support the assembly process. The system utilizes visual cues for the bin-picking action in the assembly process, guiding users with step-by-step instructions to perform tasks more efficiently, thereby reducing cognitive load and minimizing errors. The prototype has two main parts: (1) the web application part and (2) the pick-by-light system.

Web application: The high-level concept of the web application consists of two different user groups to accommodate the industrial practice of the case study. First, the kind of users are the *supervisors*, these supervisors have access to the order and order specification modifications pages to carry out all details. The prototype automatically creates a set of articles to be picked once the order specifications are added to the database according to the design requirements of the model. The *finishing technicians* the second type of users are allowed access only to the order specifications page and the picking list page that is created automatically based on order specifications, the picking list page helps guide the finishing technicians to pick the carpentry hardware step by step by pressing buttons to move forward with the following steps. The finishing technicians do not have access to any other pages to improve the intuitiveness of UI and to maintain the relevance of the work being performed.

Pick-by-light system: This system consists of a microprocessor system to controls the lighting systems. The picking list page consists of articles maps to the articles in the bins shelf. The mapping of the articles leads to the relevant LED associated with the article bin lighting up indicating the bin-picking process. Similarly, relevant LEDs light up based on the article being indicated in the picking list page in real-time.

The combined assistive system is expected to provide an intuitive and user-centric assembly process for the industry. The schematic higher-level concept representation of the prototype is represented in the figure as shown above in 4.5.

4.4.2 Low Fidelity Mockups

Low-fidelity mockups are simple and rough depictions of the end product that are conceptualized during the design phase. These low-fidelity mockups offer the advantage of quick prototyping during the early stages of the development process. They typically focus more on structure, functionality, and user flow rather than detailed visual design or interactive elements. Bohn et al. [85] highlighted the use and advantages of low-cost, low-fidelity prototypes for preproduction testing, noting their high responsiveness to the dynamic nature of the development process.

Braga et al. [86] also explored the numerous benefits of low-fidelity mockups during the early stages of the design and development process of products. They found that the use of low-fidelity models resulted in the reduction in time for identification and interaction of critical parameters of the designing process such as product performance, functionality, usability, and accessibility, and helped receive useful user insights and contributions for the redesign of the prototype. Brown and Katz in their work [87] mention about the maximum effectiveness of these low-fidelity mockups obtained during the ideation stage of the designing process, while the actual prototype could be more effective in the implementation stage of the incremental innovation based on the user-centric design process, also known as the design thinking process. The users are involved throughout the stages to attempt to generate new ideas and verify feasibility. The step-by-step designing process of the assistance system using a low-fidelity approach of prototyping is described by Brooks et. la [88].

Since the functionality of the prototype was to be made clear through the use of low-fidelity mockups the basic layout diagrams of UI are being presented. The first process of the UI of the assistance system is to authenticate the users (refer to 4.6). Authentication of users is primarily required as a security mechanism [89]. It is also necessary to control access, personalization, and accountability. The authentication process helps us to differentiate the two different kinds of users i.e. the *supervisors* and *finishing technicians*. This user authentication step helps to redirect access.

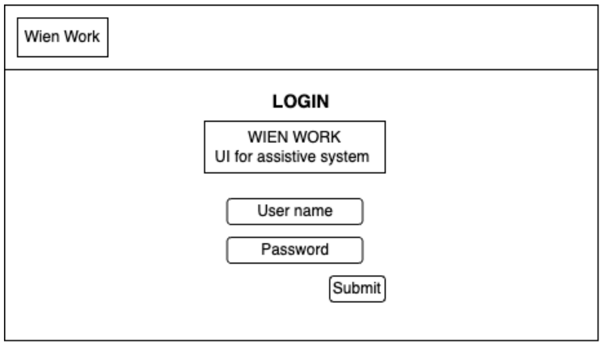


Figure 4.6.: Low fidelity Mockup: Authentication view

The main page views of the *supervisor* are the customer data page and the order page of the web application that acts as a Customer Relationship Management (CRM) application necessary for the supervisor to coordinate the production process. The *customer models* act as a one-to-many relationship with the *order models*. Each of these pages would be equipped with the option to modify the data present in the databases i.e. adding data, updating data, deleting data. The primary keys of the customer and order models are used as hyperlinks to point to the corresponding related models, refer to the low-fidelity layout of the web page 4.7.

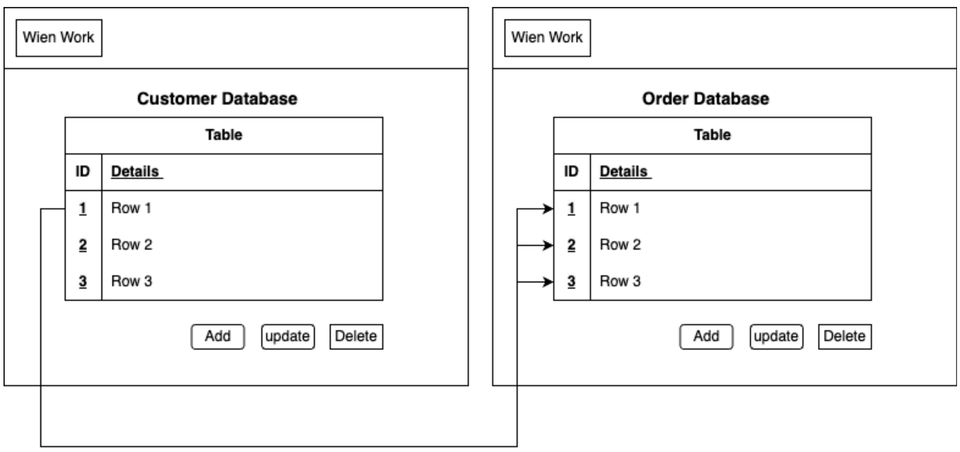


Figure 4.7.: Low fidelity Mockup: Superisor's view CRM type

Similar to the one-to-many relationship between the customer and the order models, the order and order specification models are related by the one-to-many relationship. The finishing technician is allowed access to the order specification page, this page contains the database of the dimensions, materials, and articles type that needs to be used for the order. The picking list page is automated to parse through the order specifications articles and generate the required picking list that is parsed step by step by the user parsing to the next article through a next button, in a way that instructs the user to pick the given hardware to carry out the assembly process refer to 4.8.

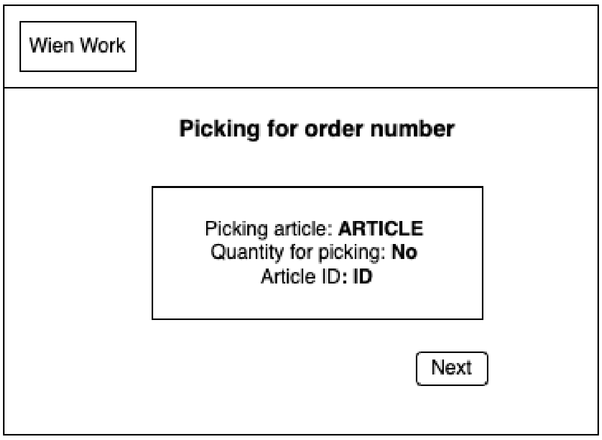


Figure 4.8.: Low fidelity Mockup: Picking page view

Finally, the UI's activities integrate with the pick-by-light system, and the picking list page also outputs an article ID of the picking hardware article. This article ID is sent to the microprocessor which scans for the bin with an article with the same article ID, if a match is found the LED is set to high (see figure 4.9), and once the technician presses next the LED is set to LOW. Similarly, the process continues until the picking process is completed. Once the picking action is parsed through the picking list, the picking page indicates that the picking process is completed.

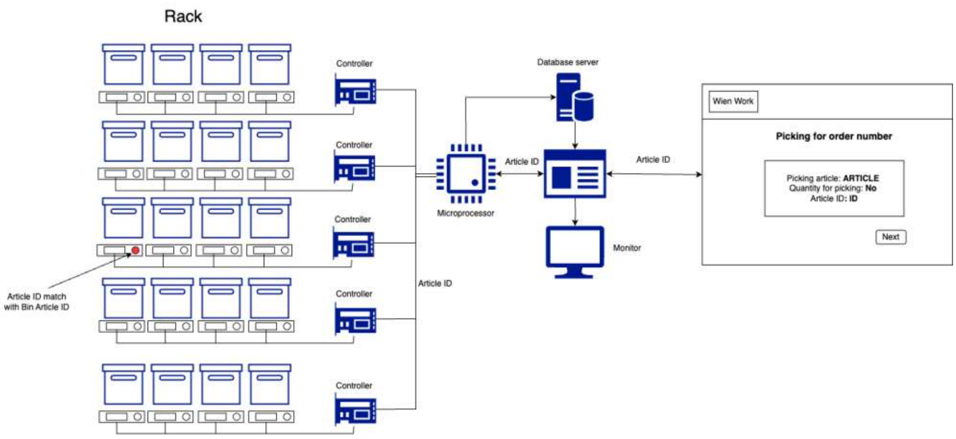


Figure 4.9.: Low fidelity Mockup: Final integrated low-fidelity assistance

4.4.3 Focus Group

The need for integrating users into the design and development process to make the assistance system human-centric focus groups were conducted to gain research insights through informal discussion methods. This method would help gain potentially varying views. The focus group data could be categorized into two main groups: content (participant's comments and views on the topic of discussion) and interaction data (participant's response or comments on other participant's comments). The study focused on collecting and analyzing only the verbal data. The conversations were only transcribed in audio-recorded format and the transcribed information has been attached in the appendix below. The audience in the focus group was the same as the people who were in the initial survey. This data was further analyzed as described in the work Nili et al. [90] mentioned.

- **Present bin picking practices**
  - What tools or methods do you currently use for bin-picking tasks, and what are their limitations?
  - What challenges do you currently experience with bin-picking processes?
  - What kind of assistive system could help facilitate the bin-picking process?
  - What are your concerns about implementing an assistive system in the current situation?
- **Prototype design**
  - How easy do you think it would be for a new user to learn this system?
  - Do you think a system like this would help you recover from mistakes or errors during the bin-picking process?
  - How easy and accessible do you think the prototype would be to use?
  - What aspects of the prototype do you find helpful or need to be improved or implemented to assist with bin picking?
  - What specific improvements would you suggest to make the prototype more effective or user-friendly in this context?

A supervisor was present to facilitate as a moderator in this situation and the data was transcribed and listed as shown in the Appendix involving table A.5.1. The listed data is structured in a way that the interaction progresses with time. Once the data have been noted easily and understandably. The next step is to analyze the available data to identify and extract meaningful user needs, and recurring themes, to ensure that the user ideas are effectively utilized in the designing process. The focus group data analysis is mainly carried out using the framework provided by the work of Nili et al. [90]. The analysis process is carried out in the order of the steps mentioned follows.

Step	Description
1	Determine and organize theoretically sensitive types of data.
2	Identify content areas.
	(For each content area:)
	3. Conduct a manifest analysis of content data.
	4. Conduct a latent analysis of content data.
	5. Analyze interaction data.
	6. Integrate the results in each content area (combine the results from steps 3 to 5).
7	Integrate and report the results of all previous steps for all content areas.

Table 4.4.: Steps of the Focus Group Data Analysis Framework

- **Step 1: Determining and Organizing Theoretically Sensitive Data**

  The considerations for this initial step have been discussed in the section above. The analysis was based on utilizing only verbal data without any consideration for the non-verbal data because the majority of the participants in the group used Austrian sign language for interaction, which was later translated by the moderator into English to be recorded. The sign language made it highly complex to analyze and the emotions and tone to be analyzed.

- **Step 2: Identifying the Content Area**

  A content area is a specific theme or topic that organizes the focus of a study, ensuring all relevant aspects of the subject are addressed systematically. The content area in this focus group consisted of the major topics of concern in this study. The focus group consisted of the following four content areas; user experience and satisfaction (i.e. customizability, user-friendliness, perceived value, etc.), system functionality and performance (i.e. accuracy, error mitigation, reliability, hardware complexity, etc.), workflow integration (system compatibility, training requirement, scalability, etc.), and accessibility and usability (assistive features, user demography incorporation, intuitive use).

- **Step 3: Conducting a Manifest Analysis of Content Data**

  After identifying the content areas, the next step is to analyze the manifest content data for each area individually. Manifest analysis of a focus group identifies and interprets explicit, surface-level content to provide clear and actionable insights. It organizes participant responses into structured themes, ensuring transparency and reducing bias. This approach focuses on what is directly stated, making findings credible and easy to trace. It helps stakeholders understand group perspectives and make informed decisions.

1. Identifying and extracting the meaningful segments of the statements made during the focus group called the meaning units (MU).
2. Condensing these meaning units into shorter phrases while maintaining the essence is called condensed meaning units (CMU).
3. Name/label each meaning unit within subthemes (codes) that share similar ideas.
4. Combine the related codes into broader themes that align with the research objective.

The manifest analysis of the content areas has been analyzed and is tabulated in the appendix section (refer to section A.5.3)

- **Step 4: Conducting a Latent Analysis of Content Data**

  Latent content analysis to explore the underlying meanings and themes within the qualitative data. By focusing on the implicit context and deeper interpretations of participant feedback, this approach provides rich insights into user motivations, challenges, and needs. Hence latent content analysis is conducted by making use of the suggested steps as follows:

  1. Extracted meaningful segments from latent content to uncover deeper insights.
  2. Simplified identified meaning units into concise descriptions while retaining their essence.
  3. Analyzed condensed units to identify their underlying significance and implications.
  4. Grouped similar condensed units into subthemes based on shared patterns.
  5. Abstracted subthemes into overarching themes to capture key insights and main ideas.

  The latent analysis of the content areas has been analyzed and is tabulated below:

Theme: User Experience And Satisfaction		
Subtheme 1: User Acceptance	**Subtheme 2: Accessibility**	**Subtheme 3: Ease of Learning**
Simple interfaces improve initial user adoption.	Accessibility considerations ensure inclusivity for all users.	Straightforward systems reduce learning barriers for new users.
The ease of use and initial understanding are key to system acceptance.	Learning may be challenging for users with disabilities or literacy issues.	Straightforward designs can simplify learning for new users.

Continued on next page

Theme: User Experience and Satisfaction		
Subtheme 1: User Acceptance	**Subtheme 2: Accessibility**	**Subtheme 3: Ease of Learning**
"Me, I don't think it is very difficult, because I see it as very straightforward to use."	"I think it might be difficult to learn a new system if they are suffering from disability."	"If the interface is simple, with a touchscreen or easy-to-read display, it should be accessible."

Theme: System Functionality and Performance		
Subtheme 1: Assistive Systems Efficiency	**Subtheme 2: Implementation Challenges**	**Subtheme 3: Stock Management**
Assistive systems improve efficiency in accessing and organizing information.	Proper training and part organization prevent implementation issues.	Real-time stock updates prevent delays.
Assistive systems could simplify design specification access and picking process.	Incorrect bin numbering or mixing parts could create implementation issues.	Indications for minimum quantity of part in the bin
"A laser system that could provide all the information about the design specifications and materials."	"It would be a problem if technicians mix up the parts or put them in the wrong bins after new orders."	"It should highlight bins that are running low on stock so we can restock before it causes any delays."

Theme: Workflow Integration			
Subtheme 1: Documentation and Tool Clarity		**Subtheme 2: Communication and Workflow**	**Subtheme 3: Operational Tracking**
Production tasks require standardized and clear documentation.	Production benefits from precise tools and pre-knowledge of parts.	Timely communication of parts usage prevents delays.	Real-time tracking enhances operational efficiency.
Basic production information is required: design plan, materials, quantity, and measurement.	Need for tools (screws, power tools) and precise prior knowledge of parts for production.	Parts used are not reported timely to supervisors for reordering.	Real time process overview could help understand the status

Continued on next page

Theme: Workflow Integration			
Subtheme 1: Documentation and Tool Clarity		**Subtheme 2: Communication and Workflow**	**Subtheme 3: Operational Tracking**
"The basic materials for production are the design plan, materials, and measurements."	"We need to know the exact parts to use for production beforehand."	"Parts are used without informing supervisors, causing delays for the next production sequence."	"If we could track progress in real-time, it would make it much easier to see how efficiently everything is running."

Theme: Accessibility and Usability		
Subtheme 1: Bin Organization	**Subtheme 2: Space and Workflow**	**Subtheme 3: User needs**
Effective bin organization minimizes confusion and search time.	Space constraints impact collaboration and workflow.	Accessibility considerations ensure inclusivity for all users.
Bins need better structuring to avoid confusion and excessive searching.	Lack of space near bins leads to inefficiencies in shared use.	It might be difficult for technicians to understand the system, how to use it, and work with it.
"The bins need to be structured properly; it creates confusion and requires a lot of searching."	"There's not enough space near bins, especially when others are also taking items."	" I'd worry about how easy it would be to use at first. If it's too complicated, it might slow us down initially. "

- **Step 5: Analyzing Interaction Data**

  Once the content analysis is completed, the next step is to analyze the participants' interaction responses. The interaction analysis is important for two main reasons: To identify points of agreement and disagreement to analyze the collective opinion, and the second reason to interpret the meaning of the participant's interaction other than agreement or disagreement to the statement. Recognizing the strengths of each agreement or disagreement (strong, medium, weak) can provide more valuable insights. To analyze the second point, examining a broad range of interaction types (such as Criticism, Fight, Challenge, Dependency, Pairing, Reference, etc.) can aid in interpreting the meaning of the response.

- **Step 6: Integrating the Results in Each Content Area**

  The following step of the analysis process is to make the data presentable and easy to understand. To accomplish this, one must organize all the subcategories, categories, themes, and subthemes within each content area into ‘subgroups’ and ‘groups’, making the content more visualizable and easier to understand. The categorized data has been tabulated:

<table>
<tr><th colspan="22">Integrated Focus Group Data</th></tr>
<tr><th colspan="5">Group 1: System, Error Mitigation, and Performance</th><th colspan="6">Group 2: System Organization</th><th colspan="5">Group 3: Workflow Integration</th><th colspan="6">Group 4: Usability, Accessibility, User Experience, and Satisfaction</th></tr>
<tr><td>Error Recovery</td><td>Session Reporting</td><td>System Effectiveness</td><td>System Efficiency</td><td>Implementation Challenges</td><td>Stock Management</td><td>Precise Identification</td><td>Structured Bins</td><td>Structured Information</td><td>Part Identification</td><td>Bin Organization</td><td>Space Constraints</td><td>Feasible Implementation</td><td>Multiple User Functionality</td><td>Real-Time Tracking</td><td>Communication and Workflow</td><td>Operation Tracking</td><td>User Support</td><td>System Usability</td><td>Accessibility</td><td>User Acceptance</td><td>Learnability</td></tr>
</table>

- **Step 7: Integrating and Reporting the Results of All Content Areas**

  The final step in the focus group data analysis process is to compile all relevant data generated through the interaction into a simple table, providing an overview of the insights derived from the user interaction. This step would help in eliciting newer requirements or making changes to the existing requirements that were initially reported. The new requirements have been listed down below for improvement and involvement of user inputs into the system.

  1. User centric design
     a) Systems with straightforward designs improve initial adoption rates and reduce learning barriers, particularly for new users.
     b) Accessibility features must ensure inclusivity for diverse users, considering capabilities such as physical disabilities or low literacy.
     c) A simple and intuitive interface, such as a touchscreen, is essential for universal accessibility and ease of use.
  2. Error Mitigation and Performance
     a) Proper system operation is critical for reliable performance and effective error recovery during tasks.
     b) Real-time progress tracking enhances operational efficiency by identifying issues early and ensuring timely corrective actions.

   c) Summary reports at the end of sessions improve accountability and ensure all items are accounted for, further reducing errors.

3. System Organization
   a) Precise part identification and prior knowledge of measurements are vital to prevent workflow interruptions.
   b) Structured bins and well-organized information reduce confusion, minimize search times, and streamline operations.
   c) Adequate space near bins is essential for smooth workflow and to prevent bottlenecks.

4. Usability and Training
   a) New users may require training to overcome challenges posed by system complexity.
   b) Simplified systems and clear workflows minimize the need for extensive training, promoting faster onboarding.

5. Workflow Integration
   a) Integration of live status updates and real-time design specifications enhances communication and operational clarity.
   b) Space planning and system integration across the organization should be carefully coordinated to avoid bottlenecks.
   c) Support for multiple users and clarity in workflow steps improve collaboration and ensure seamless operations.

4.4.4 Prototype development

To develop an assistive system to cater to specific human needs in industrial setups an approach for an instructive assistive system was made. The prototype was developed to build on repetitive iterations through user stories to satisfy and accommodate all the requirements.

The system comprises two key components. The user interface offers instructive guidance to assist users in performing their tasks efficiently. Complementing this, the interactive assistance system supports users in executing specified procedures, ensuring accuracy and ease of operation. Together, these components should enhance the overall user experience by providing both clarity and practical assistance.

4.4.5 Overview and architecture of User Interaface

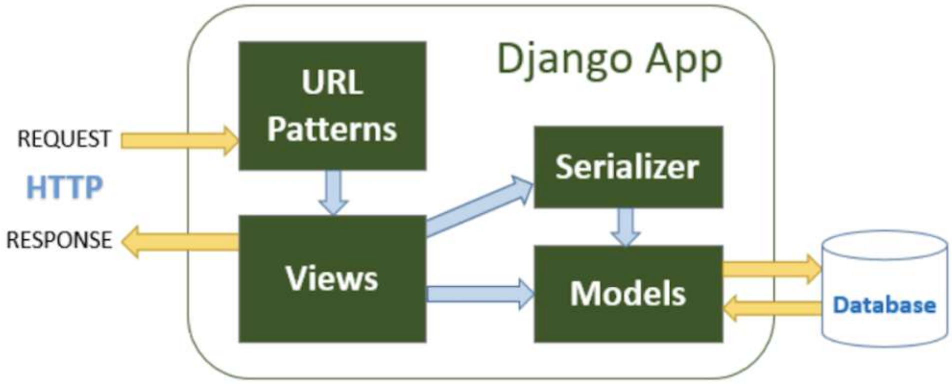


Figure 4.10.: Overview of a prototype Web App

The initial concept for prototype development involves the basic creation of a web application for the user interface, along with a database framework (using database management systems such as MySQL, Oracle, or SQL Server) for the backend. This will manage the entry of products, tools, and equipment required for the production process, as discussed in the sections above. The web application (Web application development software similar to Django, or GUI library such as PyQt, or Kivy) considers all the factors that are identified for an intuitive interface.

The prototype for the user interface in this work has been developed using *Django*, a high-level Python web framework that facilitates the rapid development of secure and maintainable websites. The web app acts as a framework to facilitate all the user interaction and accommodates all the UCD considerations. *MySQL* is used as the backend for the user interface; it is an open-source relational database management system. This section explains in detail the architectural considerations and provides more information on the technologies and procedures used for the creation of the prototype.

Django Chen et al. [91] describe Django as a powerful and flexible web development framework that has become crucial for building modern web applications. Django is a Python-based framework known for its pragmatic design, clean code, and a rich set of built-in features that accelerate the software development process [92]. The framework follows the 'Don't Repeat Yourself' principle, which promotes writing concise and maintainable code by avoiding redundancy. Additionally, Django incorporates the Model-View-Controller (MVC) architectural pattern, which ensures a clear separation of concerns, simplifying both the creation and maintenance of the system. Object Related Mapping (ORM) is a key mechanism in Django, which simplifies database interactions by eliminating the need for complex SQL queries [91]. Furthermore, Django comes with an extensive set of preinstalled tools and libraries that address various aspects of web development, including user authentication, security features, and a wide range of reusable components.

MySQL is one of the most popular relational databases, MySQL has many advantages over other Database management software because of its free and open source, and it consists of an extensive support community with rich documentation, tutorials, libraries, and tools [93]. MySQL additionally provides high-speed performance and also offers a high level of scalability to facilitate a growing database without any significant changes in performance. MySQL also offers small size, high efficiency, simplicity and ease of use, and abundant resources. Its compatibility with various programming languages, operating systems, and development environments further enhances its flexibility. Additionally, MySQL offers robust security features, including data encryption, user authentication, and access control, making it ideal for applications that demand high levels of data protection.

4.4.6 Development of User Interface:

The UI generated consists of a frontend which is designed by using the Django web application framework and Bootstrap an open source for HTML, CSS, and javascript design templates, it has a very responsive and structured styling approach that streamlines the WCAG accessibility guidelines. These considerations help maintain consistent and seamless data rendering across different UI pages. Bootstrap's grid-based system approach helps create an adaptable user-friendly interface for screens of different resolutions and sizes.

The color scheme and typographies were also customized within Bootstrap's framework to avail the AA contrast standard suggestion for the Web applications, which helps maintain the readability and contrast for users with varying visual needs. Django's form handling paired with Bootstrap's form components helped to ensure that the input fields for the users are intuitive. The Bootstap's message features were also used to give the users feedback, and validation, and make using the UI intuitive. These considerations made the resulting UI modular, and a design that balances functionality and aesthetics provides users an engaging and WCAG complement and accessible UI. The overview of the front end of the UI is provided in Figure 4.11.

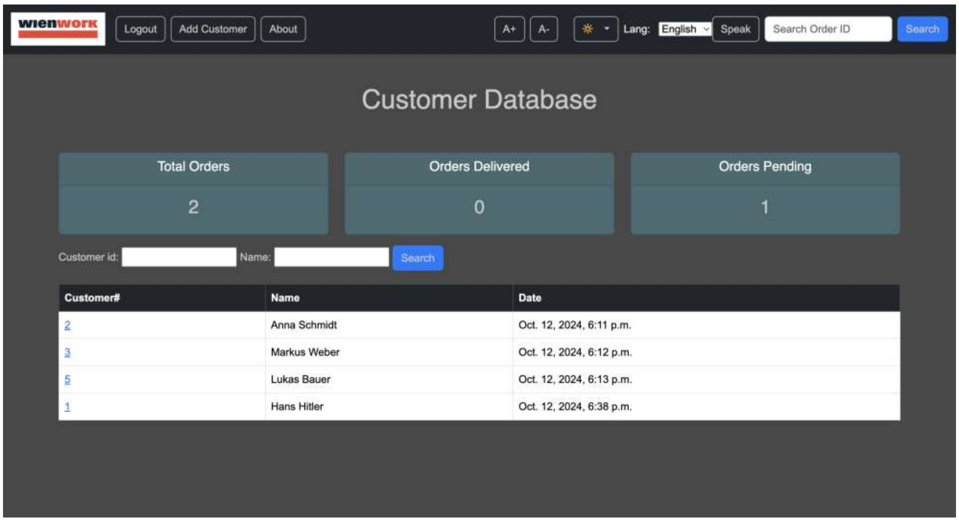


Figure 4.11.: Overview of UI frontend design

The user interface is a critical component of the assistance system discussed in the work, the UI acts as the primary point of interaction between users and the bin-picking assistive application. The UI being developed is intended to cater to facilitate users' needs by offering a smooth, responsive experience, minimizing complexity, and enabling users to achieve their objectives quickly and intuitively. This section outlines the key functional requirements generated by the previously conducted literature review and the initial survey that guide the UI's development, focusing on usability, accessibility, and efficiency to enhance overall user satisfaction and effectiveness. The different functional requirements stated in the previous sections 4.1.1 are justified and the underlying methodology is discussed in the section follows.

Accessibility:

The UI web applications have been developed with the accessibility criteria outlined in the Web Content Accessibility Guidelines (WCAG). The considerations necessary to conform to the WCAG guidelines are mentioned in the table 2.2.

The web application prioritizes accessibility for users with diverse needs, particularly individuals with hearing and visual impairments. To address visual accessibility, a screen reader feature has been integrated into the navigation bar using JavaScript's Speech-Synthesis Application Programming Interface (API). This feature reads out webpage content and includes controls for play and language options. Integrated with Django's static files, the screen reader ensures an inclusive user experience.

In compliance with accessibility guidelines, visual cues are complemented with textual labels and icons, ensuring functionality isn't reliant on color alone. The application adheres to WCAG conformance level AA, a standard suitable for industry use. The user interface (UI) design incorporates adequate color contrast, verified using a color contrast analyzer, to ensure clarity for users with color vision deficiencies.

To enhance compatibility and structure, semantic Hypertext Markup Language (HTML) markup is used throughout the application, improving screen reader navigation. CSS stylesheets are maintained separately in a static folder, ensuring a clean separation between content and design. Accessible Rich Internet Applications (ARIA) roles and labels are applied to custom elements, further enhancing accessibility and usability.

The application supports natural language usage by setting English ("en") as the default language. Additionally, a multilingual feature is available through a dropdown menu in the navigation bar, allowing users to switch between English and German. This functionality ensures content is understandable for diverse user groups and enhances accessibility.

In alignment with WCAG guidelines, tables are designed to remain readable on various screen sizes. Table headers are defined using <th> tags, and the scope attribute is applied to aid screen readers in interpreting table structures. These practices ensure a consistent and accessible experience for all users.

Content and orientation information are thoughtfully organized. Related content is grouped into dedicated pages, with page headers and labeled columns improving user navigation. A site map is provided at the bottom of the website, offering an additional navigation aid. To further simplify navigation, the application ensures consistent placement of navigation elements, breadcrumb trails to indicate users' location, and a search bar for quick access to content. Descriptive link text clarifies destinations, making navigation intuitive.

Lastly, the application prioritizes clarity and simplicity in its documentation and UI design. Information is presented succinctly, using straightforward language to ensure easy comprehension. Onboard summaries of orders provide a quick and accessible overview for users, further enhancing the overall user experience.

To address the cultural and ethnic considerations the UI is equipped with multiple languages to accommodate the workers in the case study. The study subjects were found to have proficiency in German and for development purposes, English has been used in the UI currently and could accommodate other languages in the future based on user needs.

Additionally, it addresses the major problems of assistive systems for User-centric design as mentioned in the section 2.5.

1. The web content accessibility guidelines answers for the described *accommodation problem*.

2. Considerations such as site map, consistent navigation elements, search bar, simple language, and content grouping, help address the *navigation problem*.

3. *Display unit resolution* is solved by providing a text resizing feature in the UI to provide the user‘s autonomy to adjust the resolution.

The UI is broadly based on data privacy and security, to address this the web application is not deployed and the entire database resides on local storage devices. The web application also is a device with authorized login credentials to access data.

4.4.7 Web Application Sitemap:

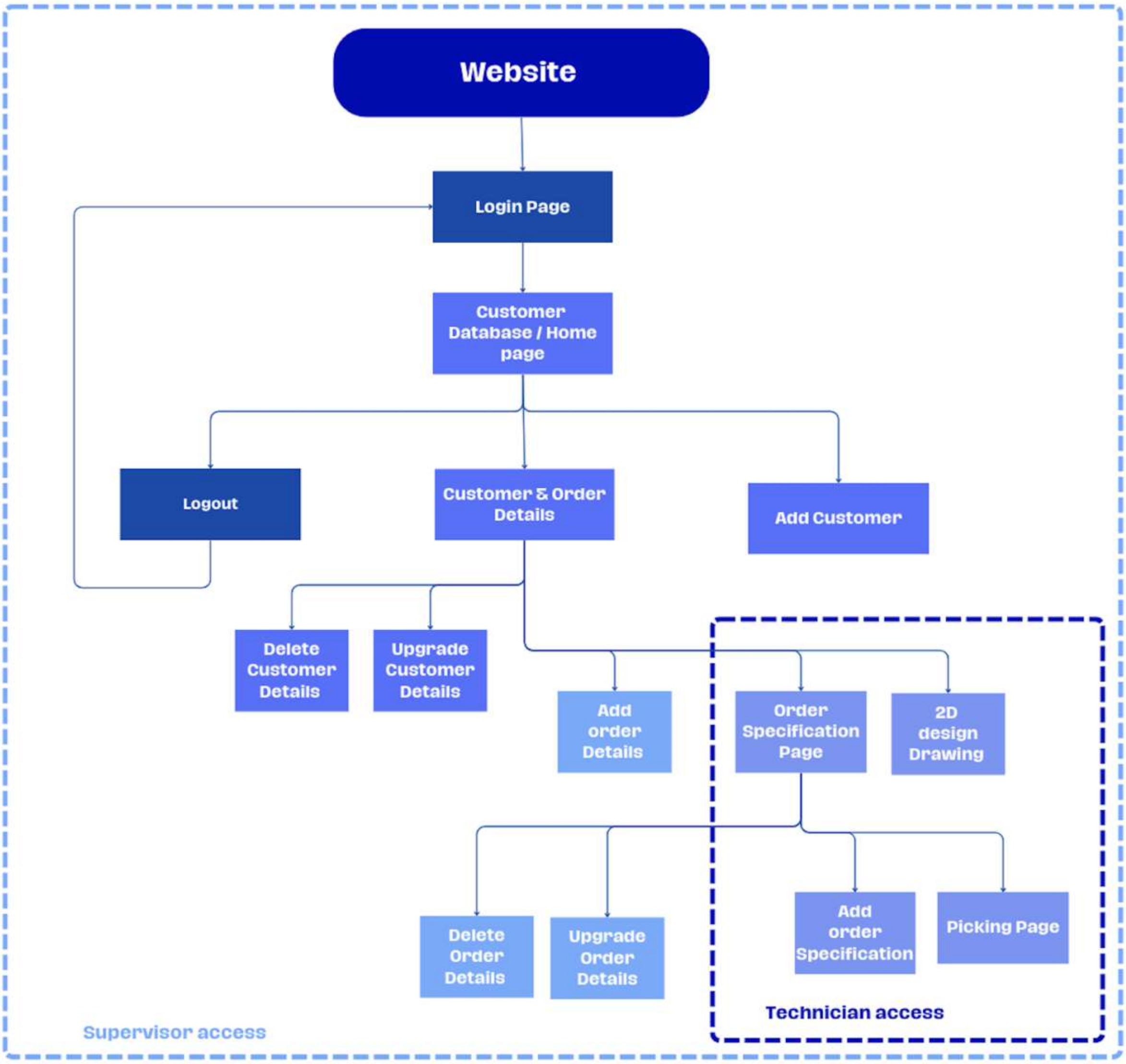


Figure 4.12.: Web application site map

The website structure features a hierarchical navigation layout, starting from a login page that leads users to the main 'Customer Database / Home Page'. Supervisors have broad access to customer and order management functionalities, including options to add, delete, or update customer and order details. A distinct section under 'Customer & Order Details' is designated for technicians, providing access to the 'Order Specification

Page' and specific functionalities such as adding order specifications, viewing 2D design drawings, and accessing the picking page. Logout functionality is directly accessible from the initial login, maintaining secure navigation for users. This organized structure ensures role-based access, facilitating efficient user navigation and task completion.

4.4.8 Prototype Github Repository

The source code of the prototype is pushed into the GitHub repository to enable collaboration and remote troubleshooting of the programs of the assistive systems. It also helps to improve the existing system to enable additional features by collaborating with multiple developers.

For the prototype code, please visit the `GitHub Repository`.

4.5 Assistance System Setup

4.5.1 Raspberry Pi

Raspberry Pi is a compact, affordable, portable, and powerful single-board computer developed by the Raspberry Pi Foundation [94], [95]. Raspberry Pi uses a designated OS called Raspbian OS, which is based on Debian. Raspbian constitutes a GUI tool that supports gaming, office work, programming, and browsing. It is also possible to use third-party OS such as Windows 10, Ubuntu, Arch Linux, etc. It possesses all the key functionalities of a full-scale computer, including the ability to browse the internet, work with spreadsheet documents, play games, and more. The Pi boards are also widely used for automation, low-cost software prototyping, education, hosting web servers, and computer applications. It offers the highest clock speed of any Pi board, along with WiFi, Bluetooth, and the capability to support multiple displays at 4K resolutions.

Nesrin et.al [96] have conducted the Web interface-based home automation using Raspberry Pi. Raspberry Pi Model B was used to control the peripheral devices. The status and measurements of the devices are published via a web interface. This application comes very close to the application studied in this work.

The board features a set of General-Purpose Input/Output (GPIO) pins, which enable data transfer, power supply, clock, and PWM functionality. It also supports a wide range of peripherals, including Serial Peripheral Interface (SPI) for high-speed data transfer, and Ethernet, which transmits both data and power over a single Ethernet cable [97].

4.5.2 WS2801 LED Strip

The WS2801 LED strip is a high-quality LED system featuring a flexible PCB. These strips include 32 WS2801 Integrated Circuit (IC)s and 32 high-quality SMD5050 RGB LEDs per meter, with each LED being individually addressable. These strips have rated IP67 waterproof rating, and with a silicon jacket, every LED can be separated into individual units containing 1 IC and I LED per segment. The LED strips can be easily driven by any ARM-based microcontroller such as Raspberry Pi, Arduino, etc [98].

Olvika et.al [99] have discussed the technical considerations for designing an effective LED panel lighting system. The datasheets of these LED strips are available which gives us more information about the operating characteristics. It is important to calculate the power supply requirements for the development. The LEDs are generally RGB-based devices. The total current for the setup can be calculated as follows.

$$I_{\text{row}} = (I_R + I_G + I_B + I_{\text{WS}}) \times W$$

$$I_{\text{row}} = (0.025 + 0.025 + 0.025 + 0.001) \times 12$$

$$I_{\text{row}} = 0.912\,\text{A} \tag{4.14}$$

$$I_{\text{all}} = I_{\text{row}} \times H$$

$$I_{\text{all}} = 0.912 \times 4$$

$$I_{\text{all}} = 3.648\,\text{A} \tag{4.15}$$

$$P_{\text{all}} = I_{\text{all}} \times U$$

$$P_{\text{all}} = 3.648 \times 5$$

$$P_{\text{all}} = 18.24\,\text{W} \tag{4.16}$$

Where:
I_{row} = current in a row
I_{all} = total current in the system
I_R = current supply for the LED's red color
I_G = current supply for the LED's green color
I_B = current supply for the LED's blue color
I_{WS} = current supply for the microcontroller
W = number of LEDs in a row
H = number of rows of LEDs
P_{all} = total power supply required for the system
U = supply voltage of the LED strip

The equation 4.14 shows the current required for the LEDs connected in series along the line. Similarly 4.15 shows the current required to be provided by the entire WS2801 arrangement to perform constant work, along with the total power requirement from the equation 4.16 would also help for the consideration of a power supply selection.

The WS2801 chips are controlled via a two-wire serial interface, with one wire handling the clock signal and the other managing the data interface. The power for the strip is controlled by two wires, one for the 5V power supply and the other for GRD to complete the circuit. It is also important to consider the serial line speed for the LED strip.

The WS2801 requires 3 bytes to set the PWM level for each of the three RGB base colors of the LED, with each color specified using 8 bits, ranging from 0 to 255. This means that each LED uses 3 × 8 bits of data for operation. Hence, the total bits of information to be transmitted are as mentioned in the equation follows.

$$B_{all} = W \times H \times 3 \times 8$$

$$B_{all} = 12 \times 4 \times 3 \times 8$$

$$B_{all} = 144\,\text{bytes} \quad (4.17)$$

where,

B_{all} = total bits of the LED system
W = Number of LEDs in the row
H = Total number of rows of LED

The equation 4.17 illustrates the amount of information that needs to be sent during each data cycle to ensure all LEDs operate at their brightest. This refers to the data transferred over the serial lines of the WS2801 chips. The number of bits to be transmitted is equal to the number of clock pulses required to synchronize the data transfer between the sender and the receiver.

The subsequent data signals from the microcontroller have a short idle time to enable the resetting of the WS2801 chips which is documented to be $t_{res} = 0.5$ ms. The application in consideration requires very low refresh rates as task completion requires a significant amount of time, optimistically refresh rates of $f_{ref} = 1$ Hz (i.e. one data cycle per second). The required serial clock rate of the serial lines from the given refresh rate can be calculated as follows.

$$f_{max} = \frac{B_{all} \times f_{ref}}{1 - t_{res} \times f_{ref}} = \frac{B_{all}}{\frac{1}{f_{ref}} - t_{res}}$$

$$f_{max} = \frac{1152}{1 - 0.005}$$

$$f_{max} = 1157.79\,\text{Hz} \quad (4.18)$$

where,

B_{all} = total bits of the LED system
W = Number of LEDs in the row
H = Total number of rows of LED

The maximum executable clock rate allowed by the WS2801 controller according to the datasheets is given as $f_{limit} = 25$ MHz, which is significantly higher compared to the f_{max} calculated above. Hence the chosen refresh rate for resetting can be feasible by the WS2801, which ensures reliable communication at the specified data rates.

4.5.3 Device Integration

Once the devices have been selected based on the preferences and requirements, the following step is integrating them to achieve the desired application. The data communication between the WS2801 LED system and the web application is facilitated through the GPIO pins, as shown below. The WS2801 LED system requires a 5V power supply (Vcc), which is connected to pin 2 or pin 4 of the Raspberry Pi 4. Similarly, the Raspberry Pi provides multiple ground pins (pin 6, 9, 14, etc.), a total of 8, which can be used for connecting the LED strip.

The WS2801 chip is managed through a two-wire serial interface. It requires a clock signal to trigger state changes or event detection, which is achieved by connecting it to the SCLK (GPIO 11) pin of the Raspberry Pi. Additionally, data flow is facilitated using the SPI (Serial Peripheral Interface), a standard protocol for serial synchronous communication in embedded systems like the WS2801 LED strip. The Raspberry Pi's MOSI (Master Out Slave In) pin (GPIO 10) is used to transfer data to the SPI device. Since the Raspberry Pi does not require data from the SPI device (the WS2801 strip in this case), the MISO (Master In Slave Out) pin (GPIO 9) is not utilized.

The GPIO pin assignments for the WS2801 chip are illustrated in the following diagram:

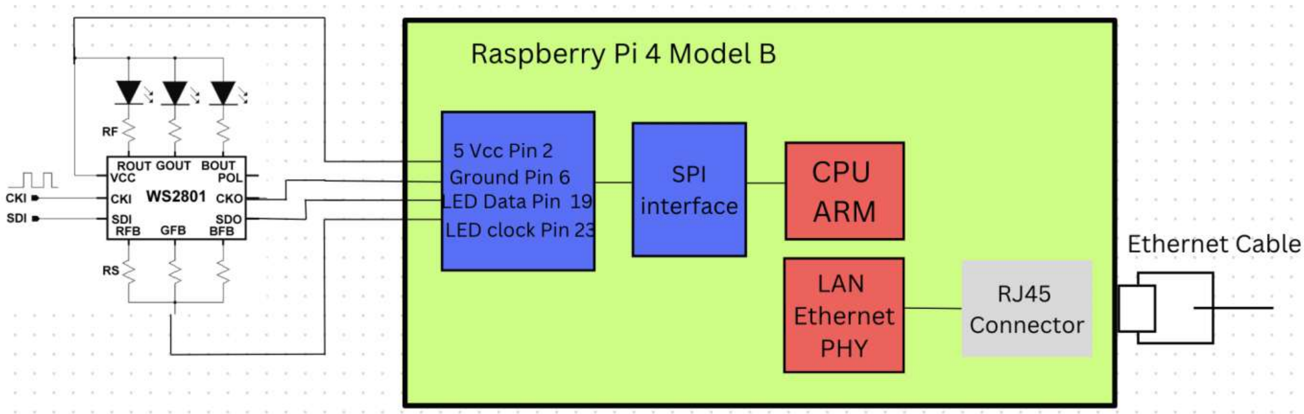


Figure 4.13.: System-level connection between WS2801 and Raspberry Pi

The picking action is performed while the user iterates through the articles on the picking iterator page. This page employs the *subprocess* module to create and manage new processes. The module enables a Python script to launch external programs (e.g., the program controlling the LEDs), connect to their input/output/error pipes, and retrieve their return codes.

The article ID and the LED indices are manually mapped in a MySQL database named *led_mapping*, taking into account the real-time locations of the assigned bins. The MySQLdb library is used to fetch the LED index corresponding to a specific article ID from the database and make it accessible to the Python program. The mapped LED index is then set to high to activate the respective LED. Here is a clear explanation of the process flow of the picking process.

The picking process begins with a user requesting the picking list for a specific order. Upon request, order data and the associated picking list are fetched from the database, and a session is initialized to track the progress of the picking operation. The system iterates through each item in the picking list sequentially to manage the order efficiently.

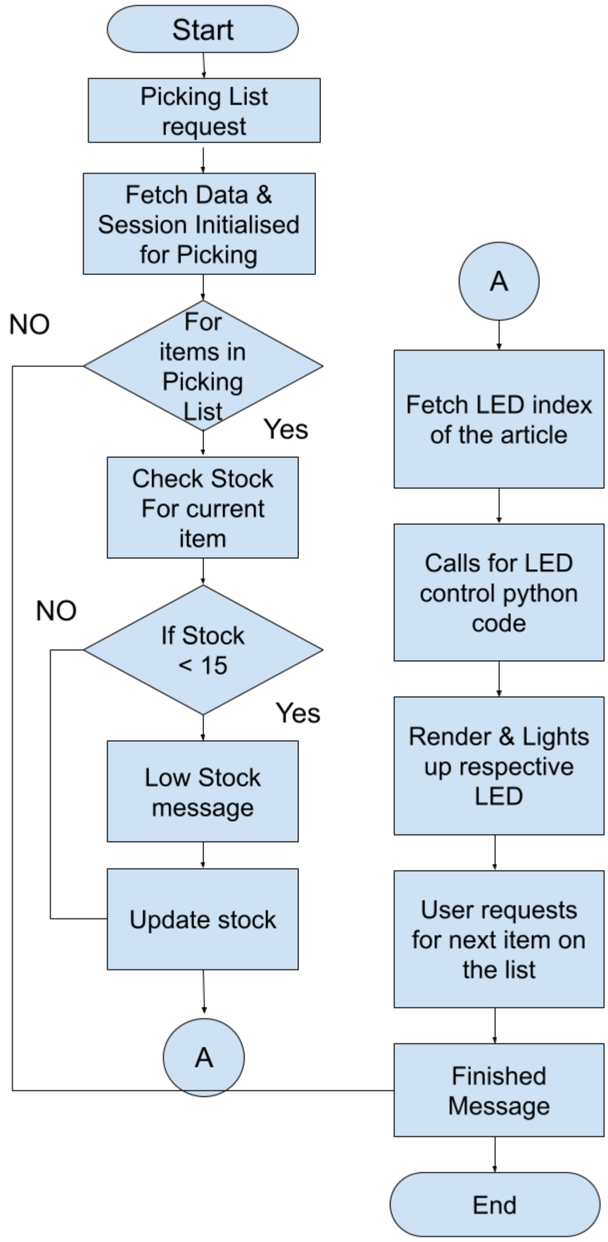


Figure 4.14.: Process flowchart of Article picking process and LED mapping

For each item, the stock quantity is checked to ensure availability. If the stock falls below a threshold of 15 units, a low-stock warning message is generated for the user. The system then deducts the required quantity from the available stock and updates the database accordingly to reflect the changes.

To help the user locate the item, the LED index corresponding to the current article is retrieved from the LED mapping table. The LED control script is then executed, lighting up the respective LED on the hardware to direct the user to the item's location. The updated picking list is displayed on the user interface, enabling the user to proceed to the next item.

Once all items in the picking list have been processed, the system displays a completion message, indicating that the operation is finished. Finally, the session data is cleared, marking the end of the picking process.

Chapter 5
Evaluation

The evaluation phase of this research focuses on assessing the effectiveness, usability, and inclusivity of the proposed assistive system through structured user testing and feedback collection. The process involves comparing the performance of the Pick-by-Light System against the traditional Paper-Based Method within a simulated environment modeled after real-world workflows. Key metrics such as usability, accessibility, ease of use, perceived efficiency, comfort level, and overall satisfaction were examined to provide a holistic understanding of the system's impact. The evaluation also draws on user feedback to generate actionable insights, ensuring that the proposed solution aligns with user needs while addressing the limitations of conventional methods.

5.1 Evaluation Setup

The evaluation was conducted using a mock setup designed to simulate typical orders processed at Wien Work's Holztechnik department. A bin-picking task, specifically for the *Endfertigung* (final assembly) operation, was selected as the basis for this evaluation. To replicate real-world conditions, 15 to 16 mock items essential for the finishing assembly were prepared and labeled accordingly.

The assistance system utilized during the evaluation comprised two main components: a WS2801 LED-based guidance system and a user interface displayed on a monitor, with input devices including a mouse and keyboard. This combination was chosen to ensure a user-friendly and efficient operation, tailored to the comfort and preferences of potential users. The evaluation compared two distinct tasks:

1. **Task 1: (Paper-Based Method)** Participants used traditional paper-based instructions to identify and pick the items required for the *Endfertigung* operation. These instructions were based on specific order specifications, representing the conventional approach to task execution.

2. **Task 2: (Pick-by-Light System)** Participants interacted with a prototype pick-

by-light system, developed based on insights from literature reviews and focus group studies. The system provided light-based cues to guide participants to the required items, aiming to enhance task performance, operational efficiency, and user satisfaction. This task exemplified a modern and assistive approach to the same activity.

To ensure unbiased evaluations, the order of tasks was randomized for each participant. This approach eliminated potential biases caused by learning effects or familiarity with the tasks. Each participant completed both tasks sequentially in a randomized order, allowing for a balanced evaluation.

The mock setup, implemented at Wien Work, provided a hands-on environment for participants to interact with the assistance system and complete the assigned tasks. The integration of the LED system with the user interface was pivotal in guiding users to the correct bins for the required components. The complete evaluation setup is illustrated in Figure 5.1.

Figure 5.1.: Evaluation setup illustrating the integration of the pick-by-light system and user interface

5.1.1 Data Collection and Interpretation

After completing both tasks, participants provided feedback through a questionnaire. A graph-based evaluation method was employed to assess various factors, such as ease of use, task satisfaction, and perceived efficiency. Each graph depicted Task 1, representing the paper-based method, on the X-axis, and Task 2, representing the pick-by-light system, on the Y-axis. Participants marked an 'X' at points that reflected their experiences in comparison with the other task. In this visual representation, marks positioned closer to the X-axis indicated higher scores for Task 1, while those

Figure 5.2.: Image of the data collection and interaction process

closer to the Y-axis signified higher scores for Task 2. Points near the diagonal suggested comparable performance in both tasks, highlighting cases where the scores for Task 1 and Task 2 were approximately equal. This layout was designed to provide an intuitive understanding of the relative performance across the two tasks, enabling a clear and effective comparison of results. To ensure clarity, each graph was accompanied by detailed explanations, helping participants understand the evaluation criteria and the purpose of the feedback.

The image 5.2 shows the actual data collection process involving the Endfertigung technicians and the supervisors at Wien Work's Holztechnik department. The data collection for the evaluation of the pick-by-light assistance system for an optimized inclusive production environment has been conducted. As discussed earlier this work aimed to assess the benefits of incorporating assistance systems by evaluating workers' experiential attributes, such as their overall user experience and satisfaction. Consents from all the participants for using their responses in the work without revealing their identity were taken.

The feedback collection included specific evaluation factors that were critical to assessing the system's performance and user experience. User-friendliness was evaluated based on how intuitive participants found the system compared to the paper-based method. Accessibility was another key factor, focusing on how well each method addressed the unique needs and requirements of participants. Ease of interaction was assessed by examining the simplicity of using the pick-by-light system in contrast to the traditional method. Perceived efficiency measured the effectiveness of each method in helping participants achieve their task objectives. Additionally, participants were asked to rate their overall comfort level when using each method, as well as their general satisfaction with the experience, highlighting any potential areas for improvement.

Beyond quantitative feedback, participants were also invited to provide personal observations and suggestions. They were encouraged to suggest potential improvements to better meet their needs and preferences. Furthermore, they were asked to reflect on the aspects of the pick-by-light system that enriched their overall experience.

5.2 Results

In the results section, addresses all the research questions formulated during the expected outcomes of the introduction section 1. The work discusses the results obtained from an extensive literature review of existing technologies and research in the field of assistive technologies, as well as the findings from the focus group data used to collect user stories and incorporate a user-centric development approach for the assistive system solution. Finally, it presents the evaluation of the developed prototype after user interaction, as outlined in the evaluation setup in the previous section. Furthermore, it also presents the results from the discussions and interviews with users of the proposed assistive system at the Wien Work's Holztechnik department, focusing on potential improvements and additions to enhance the effectiveness of the assistance system and its interaction with users. Once all this information was collected, the data was analyzed and sought to derive insights from the evaluation outcomes.

The results presented in the box plots provided from the figure 5.3 clear evidence of the comparative performance between the traditional Paper-Based approach and the Assistance System across six key metrics: usability, accessibility, ease of use, perceived efficiency, comfort level, and overall satisfaction. The findings are detailed below with their respective scores and inferences integrated for clarity.

The Usability scores for the Paper-Based system range from approximately 4 to 8, with a median of around 7. This wide range indicates inconsistency in how users perceive its usability, likely due to individual differences in familiarity with the system or its inherent limitations. By contrast, the assistance system scores are clustered tightly between 8 and 10, demonstrating not only significantly higher usability but also greater consistency. This suggests that the system is intuitive and designed to increase the ease of use, enabling users to complete tasks more easily and reliably.

In the case of accessibility, the paper-based approach score ranges from 6 to 9, with

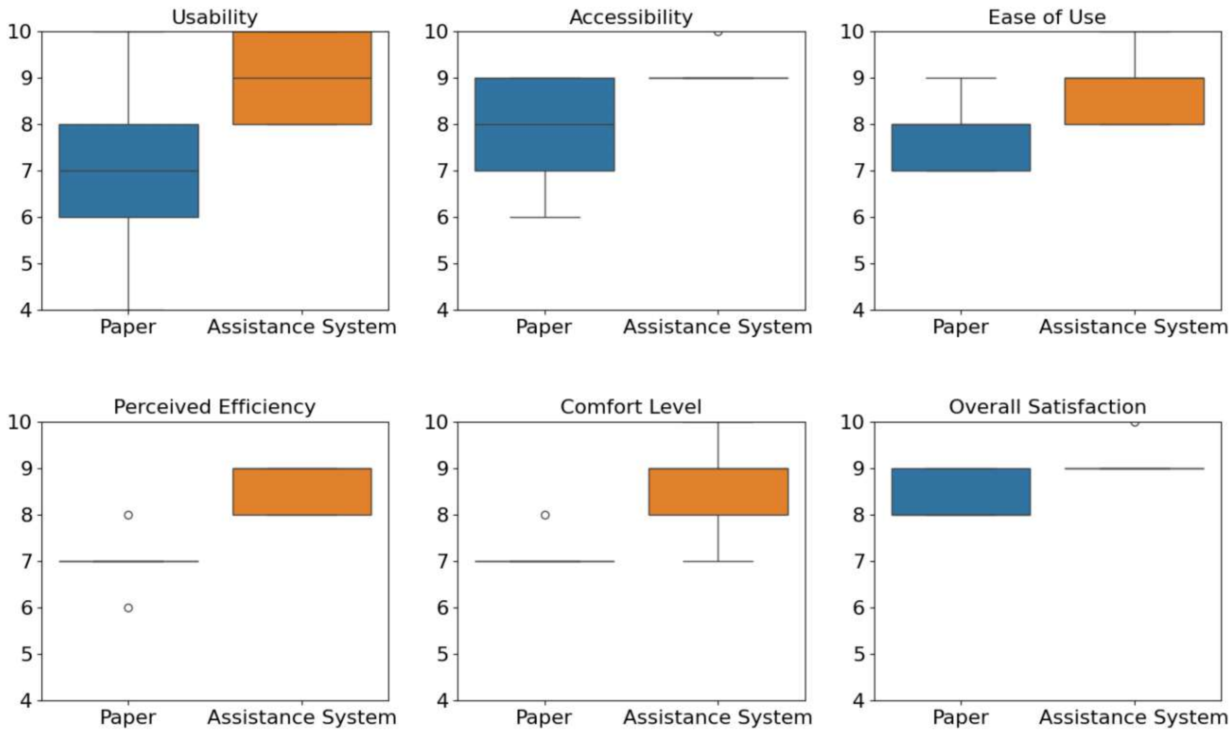


Figure 5.3.: Box plot representations of the Evaluation data

a median of about 8. However, the variability in scores and lower bounds suggests that certain users may encounter challenges in accessing or navigating the system. On the other hand, the assistance system achieves scores consistently above 9, with minimal variability and an outlier even exceeding 10. This indicates that the system has been designed to cater to a broad range of user needs, potentially incorporating adaptive or inclusive design elements that enhance accessibility for all.

Ease of Use scores for the paper-based approach are relatively concentrated between 7 and 8, with a median of around 8. While this shows that the system is functional, it also suggests that users may encounter occasional friction when completing tasks. The assistance system improves on this, with scores ranging from 8 to 9 and a higher median, indicating a more seamless and user-friendly experience. This improvement likely stems from automated or streamlined features that reduce the complexity of interactions.

The perceived efficiency metric reveals a stark contrast. For the paper-based system, scores are distributed between 6 and 8, with a noticeable outlier as low as 6, pointing to inconsistent performance. This variability may be linked to the manual nature of the system, which could slow down task completion for certain users. In contrast, the assistance system scores consistently between 8 and 9, with virtually no outliers. This reflects users' perception that the system significantly enhances efficiency by simplifying workflows and reducing redundancies.

Comfort level scores for the paper-based approach are generally low, ranging from 7 to 8, with some outliers below the lower bound. This suggests that the traditional system imposes a physical or cognitive strain on users, which can impact their overall comfort. By comparison, the assistance system scores are higher, ranging from 8 to 9.5, with a median above 9. The broader but positively skewed distribution reflects the system's ability to accommodate diverse user preferences while minimizing discomfort through thoughtful design and ergonomic considerations.

Finally, overall satisfaction scores encapsulate the users' overall experience with both systems. The paper-based system achieves scores between 8 and 9, reflecting a generally favorable perception despite its limitations. However, the assistance system excels in this metric, with all scores exceeding 9 and clustering tightly around the upper end of the scale. This indicates that the system not only meets but often exceeds user expectations, providing a cohesive and highly satisfactory experience.

5.3 Key Observations and Inferences

The results clearly demonstrate that the assistance system outperforms the paper-based approach across all metrics. The usability and comfort level metrics show the most significant improvements, with the assistance system providing an intuitive and ergonomic user experience. The consistently high perceived efficiency and overall satisfaction scores highlight the system's ability to streamline tasks, eliminate inefficiencies, and deliver a holistic improvement in user experience.

The reduced variability in scores for the assistance system also suggests that it caters effectively to a diverse range of users, ensuring inclusivity and adaptability. By contrast, the variability and lower scores in the paper-based approach reveal its limitations, such as inconsistent usability, challenges in accessibility, and reduced efficiency, which could stem from its reliance on manual processes.

These findings underscore the importance of technology-driven solutions in optimizing user experiences. The assistance system, by leveraging better design and functionality, not only addresses the shortcomings of the traditional system but also sets a benchmark for usability, efficiency, and satisfaction. Its ability to deliver consistent performance across diverse metrics and user groups makes it a compelling alternative to the traditional paper-based approach to information presenting in industries.

Chapter 6
Discussion

The discussion chapter synthesizes the findings from the evaluation to address the core research questions, drawing implications for system design, user experience, and industrial applicability. By analyzing the comparative results of the assistive system and traditional methods, the chapter explores how user-centered approaches can bridge gaps in accessibility, efficiency, and user satisfaction. Key observations are contextualized within broader industry challenges, particularly those faced by workers with disabilities, highlighting how tailored assistive technologies can foster inclusivity and productivity. Limitations and user feedback are also examined to propose future improvements and adaptations, ensuring the system's scalability and relevance in dynamic production environments. The discussion chapter also discusses on the answering the research question and the findings of the thesis work in detail.

Research Question 1: What are the challenges in integrating assistive technologies in manufacturing, and how can stakeholder involvement address these challenges?

The integration of assistive technologies in manufacturing faces several challenges, including user acceptance, accessibility, adaptability to existing workflows, and alignment with industry standards. A key factor in overcoming these challenges is the application of user-centered design, as outlined in ISO 9241-210, which ensures that systems are developed based on real user needs and practical constraints.

One major challenge is accessibility, as assistive technologies must accommodate diverse user abilities while remaining effective in dynamic industrial environments. To address this, systems should comply with internationally recognized accessibility standards, including the Web Content Accessibility Guidelines WCAG and the World Wide Web Consortium **W3C!** (**W3C!**) Web Accessibility Initiative WAI. These frameworks provide structured principles for designing inclusive digital interactions, ensuring that information is perceivable, operable, understandable, and robust across different user needs.

Another challenge lies in ensuring ease of use and seamless integration into workflows. Assistive systems must be intuitive and provide relevant support without disrupting established processes. Well-structured UI designs should follow best practices outlined in accessibility frameworks to enhance usability for all workers, including those with disabilities.

Stakeholder involvement plays a crucial role in addressing these challenges by facilitating an iterative development process. Engaging workers, supervisors, and industry experts throughout the design and testing phases helps refine system functionality, ensuring alignment with user expectations and operational requirements. Additionally, structured training and onboarding programs can improve user confidence and acceptance, particularly for individuals with disabilities.

In conclusion, the challenges of integrating assistive technologies in manufacturing can be effectively addressed through user-centered design, adherence to established accessibility guidelines such as WCAG, W3C-WAI, and WAI-ARIA, and continuous stakeholder engagement. These factors ensure that assistive systems enhance productivity, usability, and inclusivity in industrial environments while maintaining compliance with international accessibility standards.

Research Question 2: What factors and strategies should be incorporated into user interface design to create an intuitive and effective interaction experience for workers with varying cognitive and physical needs?

Integrating the WCAG into the design of assistive systems is pivotal for developing inclusive and accessible user interfaces that effectively cater to individuals with diverse abilities. WCAG principles provide a robust framework for accessibility, focusing on key elements such as offering alternatives for auditory and visual content, ensuring compatibility with assistive technologies like screen readers, and avoiding the exclusive use of color to convey information. These principles ensure that interfaces are not only accessible but also intuitive for a wide range of users.

To enhance usability, WCAG emphasizes consistent use of markup and style sheets, multilingual support, and responsive designs. Features like accessible tables, breadcrumb trails, descriptive link text, and intuitive site maps are integral to improving navigation, enabling users to efficiently locate and interact with content. Simplicity and clarity are prioritized by adopting minimalistic designs, straightforward language, and modular layouts, which collectively reduce cognitive load while enhancing the overall user experience.

Adherence to WCAG AA standards was achieved through the use of tools like color contrast analyzers and semantic HTML validators. These tools ensure high-contrast, visually distinct, and screen reader-compatible design elements, fostering inclusivity and usability. Additionally, survey findings and focus group interactions highlighted the necessity for minimal yet highly effective UI features. Users emphasized the importance of interfaces that limit interaction complexity while providing informative and automated front-end solutions.

By integrating WCAG principles and insights from target users, assistive systems can achieve adaptability, user-friendliness, and inclusivity. Such designs not only meet accessibility standards but also foster equitable access in diverse production environments, enabling seamless interaction and enhancing productivity for all users, regardless of their abilities.

Research Question 3: Which system and considerations could support assembly workers at Wien Work and how do they perceive the developed solution in the context of usability and usefulness?

The development of an assistive system for assembly workers at Wien Work followed a structured process to ensure it met user needs and improved workflow efficiency. The research began with an in-depth work analysis and requirement collection, where workers' daily tasks, challenges, and interactions with existing methods were assessed. This phase identified key limitations of traditional paper-based instructions, such as inefficiencies, difficulties in updating content, and accessibility barriers for workers with disabilities.

To guide the selection of the most suitable assistive technology, the method proposed by Mark et. al. [16] was used, ensuring that the system addressed the practical constraints of the workplace while aligning with technological advancements. This method helped evaluate potential solutions based on criteria such as ease of implementation, user adaptability, and support for interaction modalities.

Following this, a focus group was conducted to refine the requirements further. Direct engagement with workers allowed for adjustments in the system's features, ensuring that it would integrate seamlessly into their workflows. The focus group data was analysed and divided into themes and codes to extract meaningful data from the user feedback. This feedback emphasized the need for an intuitive interface to establish comfortable work environments.

Based on these insights, the assistive system was developed, incorporating features such as interactive guidance, task-specific instructions, and accessibility enhancements. The design aimed to improve efficiency while ensuring that all workers, regardless of their experience or ability, could use the system comfortably.

The system was subsequently evaluated through usability testing, where users compared it to the traditional paper-based method. The evaluation focused on user perception, experience, and satisfaction, assessed through structured questionnaires that presented graphical comparisons of both methods in the bin-picking process.

The results of the usability evaluation indicate that while the assistance system outperformed the paper-based system in most metrics, a clear user preference did not emerge. The assistance system achieved higher scores in usability, accessibility, and perceived efficiency, demonstrating its potential for improving user experience. It was also noted that workers with disability tended to vote a lower score for the assistive system. This may be attributed to the reason that they are more resilient to change due to the challenges they would encounter using a newer system. It showcases the need for conducting training and resource material to enable workers with disability to make themselves comfortable with the system, which would increase their acceptance as a result of familiarity with the system. However, it was noted that the inability to fully tailor the system to the specific needs and conditions of the workplace could have also influenced the not-so-significant improvement of the scoring of the proposed solution over the traditional paper-based instruction system. This disconnect, coupled with users' familiarity and comfort with the traditional Paper-based System, likely contributed to the mixed feedback. Although the Assistance System showcased significant improvements in several areas, it failed to resonate as strongly with users as anticipated, underscoring the importance of tailoring such systems to the practical realities of the workplace.

While the developed assistive system demonstrated clear improvements in several key areas, its adoption was hindered by the lack of seamless integration into existing work practices. The findings emphasize that successful implementation requires not only technological advancement but also strong alignment with user expectations and workflow habits. Future refinements should prioritize customization, worker training, and iterative improvements to ensure that assistive systems are both effective and widely accepted.

6.1 Limitation and Future Directions

While this study demonstrates the potential of user-centered assistive systems for inclusive production environments, several areas remain for further exploration and development. Addressing these areas will ensure the system's scalability, adaptability, and broader applicability in real-world industrial contexts.

One of the primary challenges was the small sample size of approximately five participants. Due to the limited availability of workers with similar roles and responsibilities, the study focused on a generalized set of tasks and accessibility considerations, reducing the statistical significance and generalizability of the findings. Additionally, the participant group consisted predominantly of workers with hearing impairments, limiting the study's inclusivity by not addressing the needs of workers with other disabilities such as physical, sensory, or cognitive impairments. Future research should expand user diversity to ensure the system meets the needs of a broader workforce, including individuals with varying disabilities and from different cultural and linguistic backgrounds. Future studies should focus on broadening the evaluation to encompass a more diverse user demographic. This includes individuals with varying disabilities—such as cognitive, sensory, and physical impairments—and those from diverse cultural and linguistic backgrounds.

Another limitation was the focus on soft metrics user feedback, such as satisfaction, experience, and usability. While these factors are essential for assessing user acceptance, the absence of quantifiable performance metrics, such as task completion times and error rates, made it difficult to objectively measure improvements in efficiency. Future studies should incorporate both qualitative and quantitative evaluations to provide a more comprehensive assessment of system effectiveness.

From a technological perspective, the development of the assistive system followed a circular, iterative process in which user requirements evolved over time. While this allowed for adaptive improvements, it also resulted in a system that was not fully tailored to the final workplace conditions. The limited customization hindered seamless integration into existing workflows, affecting its acceptance among workers. Future work should focus on creating more flexible and adaptive systems that can be easily customized to different workplace environments.

Another major challenge identified during the test run was a pronounced familiarity bias among workers with disabilities, who remained strongly attached to traditional paper-based methods. This resistance to change significantly hindered the acceptance of the new digital system. Alongside the lack of system-specific training materials, the findings suggest that the broader challenge lies in the general introduction of new technology to a workforce accustomed to conventional practices. Future research should therefore explore comprehensive strategies to enhance overall technology acceptance, such as change management initiatives, demonstrative presentations of the benefits of digital tools, and gradual integration approaches to facilitate a smoother transition from legacy systems.

Despite its advantages over traditional methods, the system faced low acceptance from workers in Wien Work's *endfertigung* department. This discrepancy may stem from the controlled evaluation setting, which did not fully mirror the dynamics of the real-world environment. To enhance real-world applicability, future studies should conduct extended field trials in actual production environments, allowing for long-term usability assessments and iterative refinements.

Long-term studies are crucial for evaluating the system's sustained impact on cognitive load, productivity, and worker well-being. These studies will also provide insights into how the system affects user acceptance and performance over time, identifying areas for ongoing improvement. Additionally, integrating quantitative metrics such as error rates, task completion times, and qualitative feedback will offer a more comprehensive understanding of the system's effectiveness.

Lastly, the findings of this study were specific to the Wien Work case, limiting their applicability to other industrial environments with different workflows and user requirements. Future research should focus on scalability, testing the system across various industries, and optimizing it for large-scale deployment. Cloud-based or mobile-compatible versions of the system could also be explored to enhance accessibility and flexibility.

By addressing these areas, future research can refine and expand upon the foundational work presented in this study, advancing the design and implementation of inclusive and user-centered assistive systems for industrial production environments.

Chapter 7

Conclusion

This study investigated the development, implementation, and evaluation of a user-centered assistive system aimed at improving accessibility, and inclusivity, and improving worker well-being for assembly workers at Wien Work, particularly those with hearing impairments. By replacing traditional paper-based instructions with a structured digital system, the goal was to enhance inclusivity while maintaining usability in an industrial setting. The system demonstrated improvements in accessibility, usability, user satisfaction and perceived efficiency, yet adoption remained mixed, with some workers hesitant to transition from familiar paper-based workflows. This highlights the need for structured training and onboarding programs to facilitate acceptance and adaptation.

A key challenge was integrating the assistive system into existing workflows without disrupting operations. While some users found it beneficial, others faced difficulties due to limited customization and a lack of real-world testing. Future improvements should focus on system flexibility to better align with workplace-specific conditions, ensuring seamless adoption across different user groups.

The study also explored the broader challenges of integrating assistive technologies in manufacturing and the role of stakeholder involvement. Findings emphasize that successful implementation requires user-centered design, adherence to accessibility standards (ISO 9241-210, WCAG), and iterative feedback from workers and supervisors. Stakeholder engagement was critical in refining system features to ensure alignment with practical needs. Additionally, effective user interface design played a key role in usability. However, minimizing interaction complexity was essential, as workers preferred straightforward digital guidance over overly customizable interfaces.

The study was limited by a small sample size, primarily consisting of workers with hearing impairments, which restricted the generalizability of findings. Future research should expand user diversity and conduct long-term field studies to evaluate system performance in real-world industrial settings. Additionally, gradual implementation strategies that introduce assistive systems alongside traditional methods can help mitigate resistance to change. Developing comprehensive training resources and interactive onboarding programs will further improve user confidence and adoption.

Despite these challenges, the research underscores the potential of assistive technologies in fostering an inclusive, adaptive, and efficient industrial environment. Addressing usability issues, refining integration strategies, and incorporating emerging technologies to further enhance accessibility. By prioritizing customization, structured onboarding, and continuous user engagement, future developments in assistive systems can create more equitable and technologically advanced workplaces for individuals of all abilities.

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Acronyms

HMI Human Machine Interaction

EC European Council

MR Mixed Reality

HCI Human-computer Interaction

UI User Interface

IoT Internet of Things

UCD User-Centric Design

TAM Technology Acceptance Model

TFQ Technology Familiarity Questionnaire

DRC Disability Rights Commission

WCAG Web Content Accessibility Guidelines

WAI Web Accessibility Initiative

AR Augmented Reality

ISO International Standard Organisation

EU European Union

WIPO World Intellectual Property Organisation

WHO World Health Organisation

ISO International Standard Organisation

CAS Cognitive Assistance Systems

SASAS Self-adaptive Smart assembly system

REBA Rapid Entire Body Assessment

CRM Customer Relationship Management

SPI Serial Peripheral Interface

MES Management Execution System

ERP Enterprise Resource Planning

HMD Head Mounted Displays

MVC Model-View-Controller

ORM Object Related Mapping

MCD Multi-User Centered Design

UX User Experience

ADA Americans with Disabilities Act

RFID Radio Frequency Identification

DOA Degree of Assistance

API Application Programming Interface

HTML Hypertext Markup Language

ARIA Accessible Rich Internet Applications

GPIO General-Purpose Input/Output

IC Integrated Circuit

RFID Radio Frequency Identification

Chapter A

Appendix

A.1 Higher Level assistance system catalogue

Assistance system	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23
Sensorial Assistance System																							
Eye Tracking	0	0	0	0	0	0	0	7	0	0	7	2	0	3	0	0	0	0	0	4	8	0	0
Smartwatch	0	0	0	0	0	0	0	0	0	2	3	3	0	3	4	5	3	0	3	0	3	3	3
Intelligent clothing	0	0	0	0	0	0	0	6	0	0	0	0	2	0	4	0	0	0	0	6	3	0	0
Physical Assistance System																							
Arm Exoskeleton	0	0	0	4	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0
Leg Support	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0
Back Support	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0
Flexible Assembly Assist Robot	0	0	0	0	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	0	0
Robot / Automats	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4	0	0
Telemanipulator /Balancer / Lifting Aid	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4	0	0
Wearable Lifting / Holding Aid	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	7	4	0	0
Ergonomic Manual Workplace	0	0	0	4	0	0	0	0	0	0	2	0	3	0	0	0	0	0	0	5	8	0	0
Collaborative robot	0	0	0	8	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	8	5	0	0
Cognitive Assistance System																							
Augmented reality (AR)	9	5	0	0	0	0	6	5	4	4	5	5	0	4	0	3	2	3	7	0	5	6	5
Virtual reality (VR)	9	3	0	0	0	0	7	5	4	5	4	6	0	5	0	3	3	6	2	0	2	7	3
Mixed reality (MR)	9	3	0	0	0	0	8	5	3	8	4	4	0	3	0	3	2	5	2	0	2	6	1
Visual computing system	0	0	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	5	0	3	0	9
Projection based assistance system	6	4	0	7	0	0	7	8	3	5	8	8	0	7	0	4	5	0	10	0	4	3	9
Smart scan glove	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	8	0	0
Smart phone	3	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	3	0
In-situ projection	0	7	0	4	0	0	5	4	4	4	3	3	0	3	0	3	2	2	3	0	5	6	3
Laser-projection system	0	6	0	0	0	0	0	0	0	5	7	6	0	7	0	4	4	0	8	0	7	6	0
Portable computer	2	0	0	0	0	0	0	0	0	3	0	0	0	2	0	0	0	3	2	0	1	4	0
Computer Assisted Instruction (CAI)	0	0	0	0	0	0	4	0	3	4	4	2	0	3	0	3	2	0	4	0	4	5	0
Pictorial Instruction	0	0	0	0	0	0	0	0	0	2	2	5	0	4	0	0	2	0	5	0	0	5	4
Voice control	0	9	0	0	0	0	0	0	0	0	0	0	4	0	0	4	0	0	0	0	4	3	0
Pick-by-light system	0	7	0	0	0	0	9	6	0	0	0	2	8	3	0	4	0	0	6	0	7	0	0

A.2 Work task analysis for relevant abilities

Category	Parameters	Assessment Rx
Relevant senses	Hearing ability	0
	Seeing ability	1
	Sense of smell	0
Physical Capability	Dexterity	1
	Strength and endurance	0
	Mobility / Ergonomics	1
Cognitive capability	Spatial ability	1
	Concentration	0.5
	Logical thinking	0
	Technical thinking	0
Personal attributes	Learning ability	0.5
	Retentiveness	1
	Responsiveness	0.5
	Independence	0.5
	Communication skills	0
	Attention	0.5
	Flexibility	0.5
	Creativity	0
	Correctness	1
	Physical safe working	0.5
	Working velocity	1
Skills	Technical knowledge	0
	Mathematical skills	0

Table A.1.: Work task analysis for relevant abilities

A.3 Worker analysis for relevant user groups

Category	Parameters	Assessment Nx
Relevant senses	Hearing ability	0
	Seeing ability	5
	Sense of smell	0
Physical Capability	Dexterity	4
	Strength and endurance	2
	Mobility / Ergonomics	4
Cognitive capability	Spatial ability	1
	Concentration	3
	Logical thinking	3
	Technical thinking	0
Personal attributes	Learning ability	3
	Retentiveness	1
	Responsiveness	2
	Independence	4
	Communication skills	3
	Attention	4
	Flexibility	2
	Creativity	0
	Correctness	1
	Physical safe working	2
	Working velocity	5
Skills	Technical knowledge	0
	Mathematical skills	0

Table A.2.: Worker analysis for relevant user groups

A.4 User consent Form

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WIEN

User Study & Interview Procedure Overview

Thank you for your interest in taking part in this user study to evaluate a prototype of a bin-picking assistance system with a user interface. Participating in this user study will involve in focus group with questions regarding the assistance system designed to facilitate the bin-picking process, and, voluntarily, providing feedback on the system's effectiveness, while we observe and record your opinions and understanding of user experience and potential areas for improvement.

All participants will be asked to briefly put forth their views on the system. Participants may also be invited to take part in a short interview to gather more detailed feedback. The data collected will be anonymized and used solely to improve the system and analyze user interactions for research purposes. All collected data will be treated confidentially, ensuring that no conclusions about your identity can be drawn.

Consent to Take Part in User Study & Interview

- I .... voluntarily agree to participate in this research study.
- I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.
- I have had the purpose and nature of the study explained to me in writing and I have had the opportunity to ask questions about the study.
- I agree to my interview being audio-recorded.
- I understand that all information I provide for this study will be treated confidentially.
- I understand that in any report on the results of this research, my identity will remain anonymous. This will be done by changing my name and disguising any details of my interview that may reveal my identity or the identity of people I speak about.
- I understand that disguised extracts from my interview may be quoted in the thesis: "Designing User-Centered Interfaces and Assistive Systems for Optimized Inclusive Production Environments" or related research papers.
- I understand that signed consent forms and original audio recordings will be stored until the thesis is successfully finished.
- I understand that a transcript of my interview in which all identifying information has been removed will be retained as part of the thesis appendix.
- I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

____
Signature, Date

CONTACT DETAILS

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Thesis Advisor: David Kostolani

A.5 Focus Group Analysis

A.5.1 Focus Group Transcript

Sl. No	Question	Participant	Response
1	What tools or methods do you currently use for bin-picking tasks, and what are their limitations?	Participant 3	The basic information materials for the production process are the furniture design plan, the material requirement in the order, its quantity, and the measurement.
2		Participant 4	The other tools are the small screws, power tools, and other checklists. The general procedure is that the customer asks for a specific design for the furniture which is communicated to us. The limitation is that we need to know priorly the exact parts to be used for the production.
3	What challenges do you currently experience with bin-picking processes?	Participant 4	The bins need to be structured properly; it creates confusion and requires a lot of searching.
4		Participant 1	The challenge is that the parts are being used and not being informed to the supervisors to be ordered in time for the next production sequence when needed.
5		Participant 2	There is also not an adequate amount of space, because the assembly is done right in front of the bins, which is also not very adequate. This causes a lot of problems if someone else also wants to take something from there.
6	What kind of assistive system could help facilitate the bin-picking process?	Participant 3	A laser system that could provide all the information about the design specifications, the materials, and the bin to be picked for the given tools.
7		Participant	I don't know of any assistance systems for this application, but if the computer has every critical information integrated in to the system it would be great.
8	What are your concerns about implementing an assistive system in the current situation?	Participant 4	It would be a problem if the technicians do not follow the bin numbering properly, in case they mix up the parts after using or put the parts in a different numbered bin after a new order comes in.
9		Participant 2	It might be difficult for technicians to understand the system, how to use it, and work with it. I'd worry about how easy it would be to use at first. If it's too complicated, it might slow us down initially.
10	How easy do you think it would be for a new user to learn this system?	Participant 2	I think it might be difficult to learn a new system if they are suffering from disability, some cannot read or write well.
11		Participant 4	I don't think it is very difficult, because I see it as very straightforward to use.
12		Participant 1	I think it is easy as well as a substitute for the current system because it can be a stop solution where everything is listed down and it is very difficult to miss or forget something in this system.
13	Do you think a system like this would help you recover from mistakes or errors during the bin-picking process?	Participant 4	Yes if it works as it is intended to do. I think it would help.

Sl. No	Question	Participant	Response
14	How easy and accessible do you think the prototype would be to use?	Participant 2	I cannot say that it is very accessible yet, I would expect it to accommodate the needs of everybody using it.
15		Participant 1	It depends on the implementation of the prototype if it is to be implemented throughout the organization. It would be very slow and difficult.
16		Participant 5	As long as the interface is simple, maybe with a touch-screen or easy-to-read display with a mouse it should be accessible to everyone.
17	What aspects of the prototype do you find helpful or think need improvement to assist with bin picking?	Participant 3	It may be problematic when there is a special part for the specific design and it is not available in the system. It could lead to problems so it would be helpful if someone could actively input new items into the list.
18		Participant 5	It should include items to facilitate if more than one person is working on the assembly process. It could be difficult to understand what is the completed process and what next should be done.
19	What specific improvements would you suggest to make the prototype more effective or user-friendly in this context?	Participant 4	I think it should highlight bins that are running low on stock so we can restock before it causes any delays.
20		Participant 5	If we could track progress in real time, it would make it much easier to see how efficiently everything is running and catch any issues early.
21		Participant 1	Having a summary at the end of the session showing what's been picked would be great. It would help us make sure everything is accounted for.

Table A.3.: Focus group transcripts

A.5.2 Content Areas

Content Area	Description
User Experience and Satisfaction	Focus on the user's perception of the system's design and value.
System Functionality and Performance	Focus on how well the system operates and its reliability.
Workflow Integration	Focus on how the system fits into existing workflows and processes.
Accessibility and Usability	Focus on how accessible and easy-to-use the system is for diverse user groups.

A.5.3 Manifest Analysis of content areas

Theme: Error Mitigation and Performance			
Category 1: Performance and Error Mitigation			**Category 2: Workflow Integration**
Code 1: Error recovery	**Code 2: Session reporting**	**Code 3: System effectiveness**	**Code 4: Real-time tracking**
Error recovery depends on proper system operation.	Summary reports improve accountability.	Effective operation enables error recovery.	Real-time progress tracking aids efficiency.
System could help if functioning as intended.	Summary at the end of the session to ensure all items are accounted for.	Yes if it works as it should. I think it would help.	If we could track progress in real time, it would make it much easier to see how efficiently everything is running and catch any issues early.

Theme: System Organization				
Category 1: Information Accuracy				
Code 1: Precise identification	**Code 2:Structured bins**	**Code 3: Structured information**	**Code 4: Part identification**	**Code 5: Bin organization**
Existing tools need precise part identification to avoid issues.	Poor bin organization and insufficient space hinder efficiency.	Production requires clear, structured information.	Lack of prior information about exact parts limits efficiency.	Poorly structured bins lead to inefficiency.
Furniture design plans, material requirements, small screws, power tools, and checklists; need exact parts beforehand.	Bins create confusion due to improper structuring; inadequate space creates difficulty.	The basic information materials for the production process are the furniture design plan, the material requirement in order, its quantity, and the measurement.	The other tools are small screws, power tools, and other checklists. The limitation is that we need to know beforehand the exact parts to be used for the production.	The bins need to be structured properly; it creates confusion and requires a lot of searching.

Theme: Usability And Accessibility					
Category 1: User Support					Category 2: System Usability
Code 1: Training and ease of use	**Code 2: User capabilities and learning curve**	**Code 3: Universal accessibility**	**Code 4: Ease of learning**	**Code 5: User accessibility**	**Code 6: Interface simplicity**
Challenges with training, ease of use, and risk of part misplacement.	System ease depends on user capabilities and initial learning curve.	Accessibility requires simplicity and inclusiveness.	System complexity may slow down learning and adoption.	Accessibility challenges for disabled users.	Simple interface design improves accessibility.
Technicians may mix parts, and new users might struggle with system complexity.	Varying opinions: Some find it straightforward; others see challenges for disabled users or initial slow adaptation.	Concerns about universal accessibility and ease of use; suggestions for simple interface (e.g., touchscreen).	It might be difficult for technicians to understand the system, how to use it, and work with it. I'd worry about how easy it would be to use at first. If it's too complicated, it might slow us down initially.	I think it might be difficult to learn a new system if they are suffering from disability, some cannot read or write well.	As long as the interface is simple, maybe with a touchscreen or easy-to-read display with a mouse it should be accessible to everyone.

Theme: Workflow Integration				
Category 1: Workflow Optimization				
Code 1: System assistive technology	**Code 2: Space constraints**	**Code 3: Implementation feasibility**	**Code 4: Multi-user functionality**	**Code 5: Real-time tracking**
Laser system for streamlined bin-picking.	Limited space hinders workflow and creates bottlenecks.	Implementation across the organization requires careful planning.	Multi-user functionality and workflow clarity needed.	Real-time progress tracking aids efficiency.

Continued on next page

Theme: Workflow Integration				
Category 1: Workflow Optimization				
Code 1: System assistive technology	**Code 2: Space constraints**	**Code 3: Implementation feasibility**	**Code 4: Multi-user functionality**	**Code 5: Real-time tracking**
A laser system to provide design specifications, materials, and bin details.	There is also not an adequate amount of space because the assembly is done right in front of the bins, which is also not very adequate. This causes a lot of problems if someone else wants to take something from there as well.	It depends on the implementation of the prototype if it is to be implemented throughout the organization. It would be very slow and difficult.	It should include items to facilitate if more than one person is working on the assembly process. It could be difficult to understand what the completed process is and what the next steps should be done.	if we could track progress in real-time, it would make it much easier to see how efficiently everything is running and catch any issues early.

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