Evaluating Human-Robot Interaction User Experiences in Manufacturing: An Initial Assessment Framework

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***Abstract*—In the manufacturing sector, enhancing user experiences (UX) in Human-Robot Interaction (HRI) and Human-robot collaboration (HRC) are becoming increasingly essential. The core contribution of this research is the development of a UX assessment framework tailored for evaluating HRI in manufacturing, including five facets of UX. Through qualitative semi-structured interviews, we focus on identifying key factors that constitute UX in the manufacturing context. This framework is derived from an in-depth analysis of user feedback, providing a structured approach to understanding user interactions with robots. Our work highlights the importance of fostering intuitive and productive human-robot relationships in manufacturing. Future research should explore diverse manufacturing environments and integrate emerging technologies to further refine and validate the framework.**

I. INTRODUCTION

In the manufacturing industry, with the increasing demand for product personalization and customization, enterprises are facing the challenge of manufacturing flexibility – i.e., managing and fulfilling diverse customer demands [1]. Faced with the requirements for small batches and high customization production, traditional fixed automation robot systems, designed primarily for large-scale and single-product production modes, often struggle to cater for these rapidly changing demands [2]. Against this backdrop, the development of smart factories provides possible solutions but urgently requires the exploration of new modes of HRI, where effective collaboration between humans and robots [3].

HRI refers to the process of communication, collaboration, and joint operation between humans and robots in a shared work environment [4]. Although the development of HRI technology (such as gesture recognition) has provided new possibilities for human-machine cooperation, existing research on HRI mainly focuses on technological challenges and solutions, with relatively less consideration of the importance of user experience (UX) [5]. UX refers to the feelings, cognition, and responses formed by users in the process of interacting with products or systems, directly affecting users' acceptance of technology, satisfaction with use, and work efficiency [6, 7].

In this study, we aim to lay the foundation for a user-cantered HRI framework to evaluate and enhance the user experienced within manufacturing environments. Employing a qualitative approach, which comprises semi-structured interviews (as depicted in Figure 1), we primarily recruited people from manufacturing factories to gather insights that directly inform the development of our assessment framework. This approach enables us to uncover and define the essential elements necessary to evaluate and improve the HRI user experience. Our primary objective is to facilitate the optimization of HRI within the manufacturing industry through the development of our tailored HRI UX Assessment Framework. The specificity of our framework ensures its efficacy as an instrumental resource for meeting the unique requisites of the industry. We posit that our methodological approach will yield theoretical and empirical guidelines for the design of HRI systems in advanced manufacturing settings, thereby contributing significantly to the discipline by promoting more effective, secure, and human-oriented interactions between robots and humans.

Figure 1 Semi-structured interviews in enterprises.

II. RELATE WORK

A. Research HCI in Manufacturing

In the manufacturing sector, HRI plays a critical role in addressing the growing demand for product customization and enhancing manufacturing flexibility [8]. It enables a more adaptable production line where robots can assist in tasks requiring precision and endurance, while humans contribute with decision-making and problem-solving skills [9]. This collaboration is vital in creating efficient workflows that can adjust to small batches and high customization demands, a common challenge in modern manufacturing processes [10].

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The effectiveness of HRI in manufacturing heavily relies on the design of user interfaces that facilitate natural and intuitive communication between humans and robots [11]. These interfaces range from visual displays, gestures, and speech to more advanced natural language and haptic interactions, each suited to different levels of interaction [12]. For instance, graphical user interfaces and augmented reality interfaces are prevalent for tasks requiring coexistence, while more complex cooperative and collaborative tasks may benefit from speech, gesture, and physical interactions [12]. The choice of interface impacts the efficiency of human-robot teams, emphasizing the need for designs that are intuitive, adaptable, and capable of supporting a seamless flow of information, thereby ensuring safety and enhancing productivity in manufacturing environments [13].

B. Role of User Experience in Manufacturing HRI

In the realm of manufacturing, integrating UX within HRI is crucial, especially as collaborative robots (cobots) become standard, designed to operate alongside humans within shared workspaces [14]. These cobots adhere to ISO safety standards [15], focusing on behaviours like speed and power adjustments based on human proximity, yet often overlook the critical role of interfaces in facilitating effective human-robot communication [3]. This oversight highlights the need for a human factors perspective in designing communication strategies that allow for intuitive and effective cooperation between humans and robots, incorporating principles from Human-Computer Interaction (HCI) and Human-Machine Interaction (HMI) to ensure that technological advancements in HRI genuinely benefit human operators [16].

The necessity of a structured human-centered approach in HRI design is underscored by the significant impact robots have on human work dynamics in manufacturing [16]. This approach should prioritize clear communication and intuitive information exchange between operators and robots, addressing not only the technical but also the cognitive and psychosocial aspects of human-robot collaboration [17]. By using a human-centered methodology aims to seamlessly integrate cobots into industrial settings, enhancing efficiency and the overall user experience by leveraging insights from qualitative HCI methods to inform interface design and interaction strategies [18].

C. Assessment of User Experience

Incorporating UX into manufacturing HRI is pivotal, enhancing operational efficiency and user satisfaction within constrained interactions [14]. In the literature on UX, various questionnaires are instrumental in assessing the multifaceted nature of user interactions with systems. Beginning with an evaluation of overall satisfaction and system usability, the Post-Study System Usability Questionnaire (PSSUQ) and the System Usability Scale (SUS) stand out for their ability to offer rapid, yet insightful metrics [19, 20]. These foundational assessments are complemented by more focused inquiries into software and interface satisfaction, as evidenced by the Software Usability Measurement Inventory (SUMI) [21] and the Questionnaire for User Interaction Satisfaction (QUIS) [22].

In the broader context of technology acceptance and comprehensive UX assessment, the Technology Acceptance Model (TAM) [23] provides a theoretical framework to predict user acceptance, while the modular evaluation of Components for User Experience (meCUE) questionnaire [24], the User Experience Questionnaire (UEQ) [25], and AttrakDiff [25] offer a multi-dimensional exploration of user experience, encompassing efficiency, stimulation, and the hedonic and pragmatic quality of HRI systems.

These tools highlight the multifaceted nature of UX in HRI, underscoring the importance of evaluating both pragmatic and hedonic aspects to enhance system design and user satisfaction. However, there is no evaluation tool that is suitable for the UX of HRI, especially in manufacturing. This reveals a gap in current evaluation methodologies, suggesting the need for a comprehensive, industry-specific UX evaluation framework that integrates diverse methods to better reflect the complexities of HRI in manufacturing settings. This farmwork can support the design evaluation of the UX of HCI tools in manufacturing in the next research step. In this paper, we aim to develop an initial HRI UX framework in manufacturing, and this framework's specificity may ensure its efficacy as an instrumental resource for meeting the unique requisites of the industry.

III. METHODOLOGY

This study adopts a qualitative approach by semi-structured interviews to investigate HRI in manufacturing environments. And based on interview, we developed a pioneering HRI UX Assessment Framework tailored for the manufacturing industry.

Research factories background

In this study, we select 3 different scales of manufacturing enterprises. Factory 1 belongs to CITIC Dicastal (the world's largest automobile wheel hub and

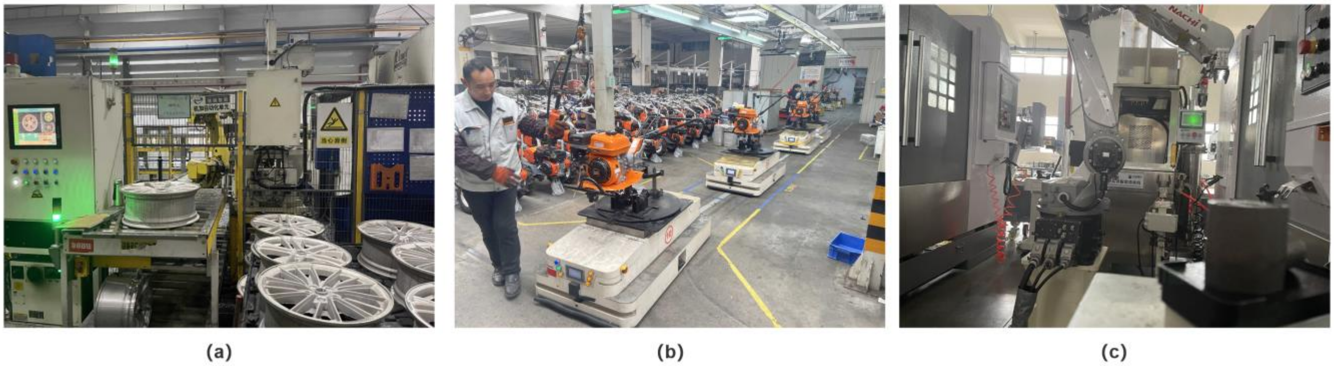

Figure 2 Pictures from the three factories where we interviewed personnel. (a) Factory 1 (b) Factory 2 (c) Factory 3

automobile chassis parts manufacturing enterprise) and JIEL joint-venture factory, shown in Figure 2 (a). Factory 2 is a small and medium-sized outdoor production machinery factory (HWASDAN), shown in Figure 2 (b). Factory 3 (KHM) is Cummins Engine's key parts supplier, shown in Figure 2 (c). The robot completes the parts processing, and the operators check the quality of the parts. And 3 factories have different levels of automation. Factory 1 achieved a high level of automation maturity with the assistance of ABB and FANC in 2009. Due to the complexity and variety of its products, Factory 2 utilizes human-robot collaboration, with workers and Chinese AGVs (Automated Guided Vehicles) jointly completing assembly tasks. However, its automation level is low, and workers are not yet fully accustomed to working alongside robots. Factory 3 focuses on precision production and has achieved complete robot autonomous production (by Nachi) in key process parts.

A. Participants

In this study, 19 employees directly involved with robotic systems, ranging from novices to experts and spanning various manufacturing roles, were selected. A comprehensive selection process was employed to include all workers interacting with robotic systems across three distinct manufacturing plants, ensuring a diverse analysis of interactions stemming from various operational roles, experience levels, and intensities of engagement with robotic technology. Participants' backgrounds vary in terms of their ages (average age is 43), education backgrounds (from high school to college), and genders (seventeen males, two females), ensuring diverse insights into HRI experiences. Table 1 shows different factory operators interact with robots in different ways and number of participants from each factory.

TABLE 1 THE WAY OF INTERACTING WITH ROBOTS

	Number of participants	Interacting with robots
Factory 1	4	After completing the task, the operators reposition the robot and changes the tool.
Factory 2	8	Operators completes the assembly task on the AGV, the AGV is sent to the next task flow.
Factory 3	7	Operators reposition robots and change tools while inspecting the quality of manufactured products.

B. Semi-Structured Interviews

The research design incorporates semi-structured interviews (an example of semi-structured interview questions is shown in Table 2) to capture qualitative insights into the experiences and perceptions of manufacturing employees regarding HRI. The interview guide was developed with semi-structured, open-ended questions to facilitate a flexible yet focused dialogue, ensuring thorough exploration of key themes such as usability, collaboration efficiency, and safety. With participants' consent, interviews were conducted and recorded audibly. The recording was transcribed into text and translated into English, and later transcribed verbatim for a detailed thematic analysis to uncover recurring patterns and insights.

TABLE 2 EXAMPLE OF SEMI-STRUCTURED INTERVIEW QUESTIONS

How do you feel about the physical interaction with the robot?
What positive and negative impacts do you think it has had?
During the operation, which parts of the robot do you find intuitive, and which parts might need improvement?
How did you learn to operate the robot?
During the learning process, which resources or methods were most helpful to you?
What specific difficulties or challenges did you encounter when you first started using the robot?
What specific changes have you noticed in your work efficiency?
What positive or negative impacts do you think robot technology has had on your productivity?

IV. RESULTS

A. Data Processing

Rich qualitative data was collected through semi-structured interviews. Analysis in NVivo 12 revealed different themes representing the aspects of HRI assessment experienced by participants. In the qualitative analysis conducted using NVivo, 28 themes were initially identified, each representing a distinct aspect of HRI pertinent to the user experience in manufacturing environments. These themes encompass critical dimensions such as 'Usability,' denoting the ease and intuitiveness of interaction with HRI systems; ‘Adaptability,' reflecting the system's ability to adjust to user and environmental variables; ‘Safety,' indicating the presence of protective measures for users; 'Efficiency,' relating to the system's contribution to productivity; along with other specific themes including 'Emotional Response,' 'Cognitive Load,' and 'Physical Ergonomics.' This comprehensive identification ensures a nuanced understanding of the multifaceted HRI user experience. Each theme was supported by direct quotes or summaries of participant responses. Ultimately, 28 themes most relevant to HRI assessment were identified.

The process of condensing the themes extracted from the qualitative dataset involved a systematic and iterative methodology [26]. Initially, open coding was employed to identify preliminary themes directly from the data. This was followed by axial coding, where these initial themes were categorized based on their relationships and relevance to the study's objectives. To ensure rigor, this coding process was conducted independently by two researchers, followed by a consensus meeting to resolve any discrepancies and to refine the themes further. Subsequently, selective coding was applied to distill these themes into broader categories that encapsulate the core aspects of HRI within manufacturing contexts. This multistep process ensured that the final set of themes was both comprehensive and aligned with the research questions, providing a structured basis for the analysis.

In the meticulous refinement of themes for the HRI UX Assessment Framework, our inquiry adopted a systematic and iterative protocol to whittle down the initial enumeration of 28 themes to a pivotal cadre of 12. This cautious process commenced with an exhaustive evaluation of the thematic occurrences across the dataset, underscored by their significance to user experience within HRI scenario. Intersecting themes such as 'Acceptance' and 'Emotion' were amalgamated to fortify the framework's conceptual cohesion, while themes that did not significantly impact UX in HRI in our study—namely 'Age,' 'Education,' and 'Price'—were excised with judicious precision to refine the framework's thematic focus. This process of distillation resulted in the retention of 12 core themes, which were then systematically incorporated into five distinct facets These facets were purposefully constructed to encapsulate the breadth and depth of the user experience in HRI, thereby providing a robust framework for the nuanced appraisal and enhancement of human-robot synergy in industrial environments.

B. *Example of Interview Data*

In the process of formulating the HRI UX Assessment Framework, interview data played a pivotal role in elucidating the critical dimensions of user experience in human-robot interaction within manufacturing environments. This section aims to illustrate the rationale behind the delineation of the framework's facets, drawing on qualitative evidence from participant feedback to elucidate the genesis of each facet. It's important to clarify that the intention here is not to re-validate the framework with the same data from which it was conceived but to provide a transparent account of how participants' experiences and insights directly informed the framework's structure (TABLE 1).

For instance, the Operational Performance Facet was informed by participants' testimonials regarding efficiency, accuracy, and reliability in robot-assisted tasks. Similarly, the Physical Interaction Facet emerged from discussions on ergonomic interactions and user comfort, highlighting the significance of physical aspects in user experience. The Cognitive Load, Emotional Response, and System Adaptability Facets were similarly developed, each rooted in specific participant feedback that underscored the importance of ease of learning, emotional factors, and system flexibility, respectively.

TABLE 3 EXAMPLES OF THE SEMI-STRUCTURED INTERVIEW IN UX ASSESSMENT FACETS

Facet	Participant Feedback
Operational Performance Facet	
Efficiency	"For the specific line it's used on, efficiency has increased by more than 30%."
Accuracy	"Previously, we had issues with the assembly line, but now, with the robots, the quality has significantly improved. The defect rate used to be around 30% before, and now the quality rate (or pass rate) is over 90%."
Reliability	"If properly trained, it's reliable. But without proper training, it can be risky, perhaps only two or three out of ten. I've heard of accidents where people were injured due to operational errors."
Physical Interaction	
Ergonomics	"The robots have significantly improved the work environment. Before, we used to work in uncomfortable postures which was quite taxing on our bodies. Now, with the robots, we work standing up, which is much more comfortable and has also improved the quality of our work."
Interaction Interface Design	"Comparing ABB and Fanuc robots, I find ABB's interface to be more user-friendly. The setup and operation require fewer steps, which saves time and makes it easier for new operators to learn."
Cognitive Load Facet	
Ease of Learning	"Learning the basics and getting the robot to operate automatically takes about a day or two."
Usability	"Using it can be frustrating. I'd rate the satisfaction as eight out of ten, as it can be quite troubling when it doesn't work properly"
Memory Burden	"Its operating interface, some primary menus, secondary menus, those are more concise, those things are easy to remember. It has some operations, some brands of robots. Some are not easy to operate, with some machine menus that you really have to press many times to enter, or some places are not easy to remember."
Emotional Response Facet	
User satisfaction	"I actually really enjoy operating it."
Trust	"I trust it quite a lot, maybe 90%."
Safety Feeling	"Our automated line is enclosed with protective barriers, ensuring safety. Once the safety doors are opened, the system automatically shuts down"
System Adaptability Facet	
Personalization settings	"About seven or eight out of ten. Different robot brands have their own unique features and functions."

C. *HRI UX Assessment Framework in Manufacturing*

The HRI User Experience Assessment Framework, through methodical analysis, integrates 12 selected themes into five rigorously defined facets (Figure 3):

Operational Performance Facet: Investigates efficiency, accuracy, and reliability of robot-assisted tasks, highlighting the critical role of these factors in optimizing manufacturing processes and outcomes.

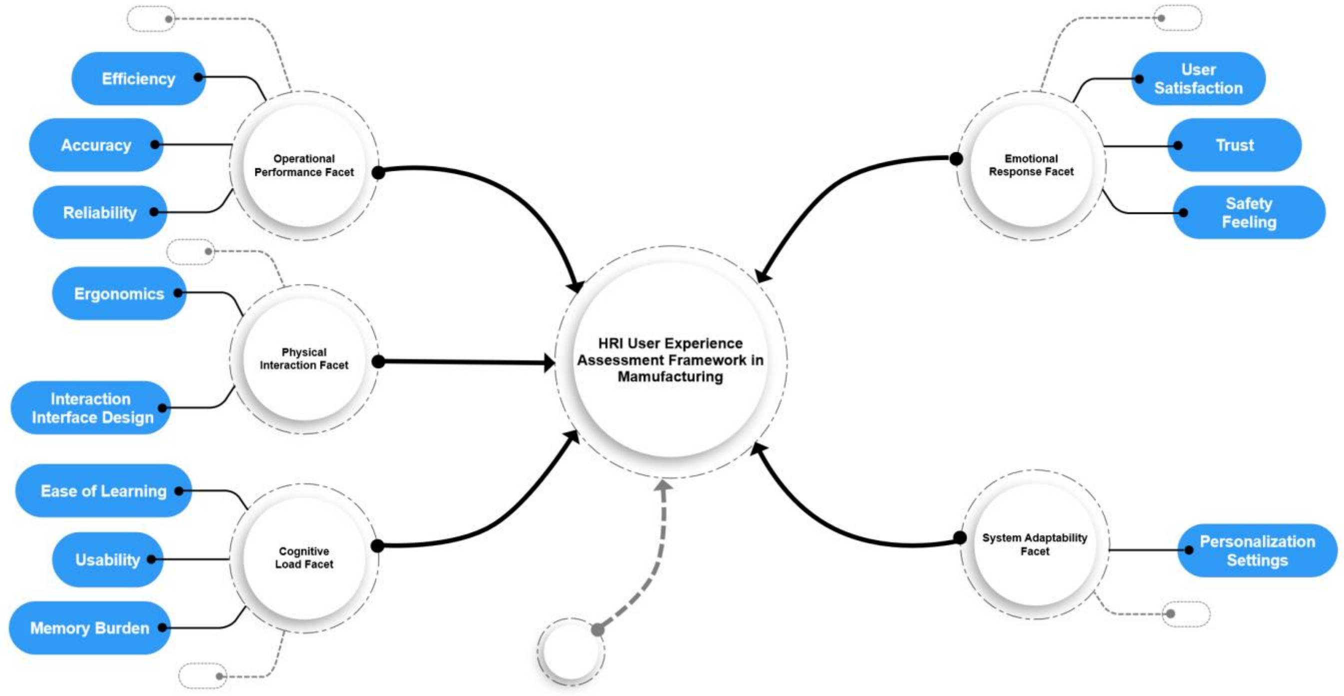

Figure 3 An HRI User Experience Assessment Framework in Manufacturing. Dotted lines represent the framework's potential for expansion to incorporate additional user experience aspects.

Physical Interaction Facet: Focuses on the ergonomics of human-robot interfaces, the design and responsiveness of interaction systems, and the importance of effective operation feedback, underlining the need for physical comfort and effective communication between humans and robots.

Cognitive Load Facet: Addresses the ease of learning, usability, and memory burden associated with operating robotics, emphasizing the significance of intuitive design to minimize cognitive strain and enhance user engagement.

Emotional Response Facet: Explores user satisfaction, trust, and safety perceptions, acknowledging the profound impact of emotional factors on user acceptance and the overall success of HRI systems.

System Adaptability Facet: Assesses the system's capacity for personalization and role differentiation, as well as the ease of conducting system upgrades and maintenance, underscoring the need for flexible and adaptable HRI systems.

V. DISCUSSION

Our exploration into optimizing HRI within the manufacturing industry, guided by our tailored HRI UX Assessment Framework, reveals critical insights into enhancing operational efficiency and worker engagement. This framework's specificity to manufacturing distinguishes it from generic models, making it a potent tool for addressing unique industry challenges.

The Operational Performance facet underscores the efficiency, effectiveness, and satisfaction derived from HRI systems. Theoretically, it challenges and extends current understandings of productivity in human-robot collaborations, The Operational Performance facet underscores the efficiency, effectiveness, and satisfaction derived from HRI systems. Interview results suggest a nuanced relationship between task performance and UX. Practically, insights into operational performance can guide the design of more responsive and intuitive HRI systems, emphasizing the balance between automation and human oversight.

Physical Interaction addresses the ergonomic and safety aspects of HRI. It highlights the importance of designing interactions that minimize physical strain and maximize safety. This facet contributes to a growing body of literature emphasizing the physical harmony between humans and robots, advocating for designs that accommodate human physical limitations and preferences [27].

The Cognitive Load facet examines the mental effort required to engage with HRI systems. suggesting that minimizing cognitive load can enhance user satisfaction and efficiency. From a practical standpoint, understanding cognitive load implications can lead to more intuitive system interfaces and interaction protocols, reducing barriers to HRI adoption.

Emotional Response captures the affective dimension of HRI, including feelings of trust, frustration, and satisfaction. We underscore the need for HRI systems to be designed with an understanding of human emotions, fostering positive emotional connections between users and robots.

System Adaptability focuses on the flexibility of HRI systems to accommodate diverse user needs and preferences. By emphasizing adaptability as a critical component of UX. The practical implications of this facet lie in the development of adaptable systems that can cater to a broad spectrum of operational contexts and user characteristics.

VI. CONCLUSION

This study developed a pioneering HRI UX Assessment Framework tailored for the manufacturing industry, marking a significant stride towards optimizing human-robot collaboration. The preliminary nature of this framework calls for further empirical validation, such as a questionnaire is designed according to this framework for verification. Future research should extend this groundwork by exploring diverse manufacturing environments and integrating emerging technologies to refine and validate the framework's effectiveness further. Ultimately, our work underscores the importance of fostering symbiotic human-robot relationships, paving the way for more intuitive, productive, and satisfying manufacturing processes.

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